

# **AERONAUTICAL TECHNOLOGIES FOR THE TWENTY-FIRST CENTURY**

AERONAUTICS AND SPACE ENGINEERING BOARD  
NATIONAL RESEARCH COUNCIL

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# **Aeronautical Technologies for the Twenty-First Century**

Committee on Aeronautical Technologies  
Aeronautics and Space Engineering Board  
Commission on Engineering and Technical Systems  
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# FOREWORD

Over the last decade, foreign aircraft manufacturers have made significant inroads into the global aircraft market, to the detriment of U.S. interests. The commuter aircraft market has been almost completely lost to foreign manufacturers, the subsonic transport market is seriously threatened, and foreign competitors are already positioning themselves to capture the future supersonic transport market.

Foreign governments, in close relationships with their aircraft industries, have invested heavily in the basic aeronautics research and technology that is necessary for developing and maintaining a competitive posture, meeting future constraints on air traffic management system capacity, and reducing the environmental impact of aircraft. This is particularly true in the advanced subsonic transport market. Although the availability of advanced technology is only one of several factors that relate to overall competitiveness, without continued access to that technology the leadership that the U.S. subsonic transport aircraft manufacturers now enjoy will continue to erode. Whereas technology alone may not ensure economic success in competition in the aircraft industry, without competitive technology, U.S. manufacturers will fail economically.

Clearly, maintenance of U.S. standing in the world industry is an imperative national need. The current effort of the U.S. government to support basic aeronautics research and technology is inadequate to meet that need. Although the aeronautics research program supported by the National Aeronautics and Space Administration contains elements that contribute to advanced subsonic aircraft technology, the funding level is well below that needed to be competitive. The threat is growing, and the nation's technological capability is not being positioned for the future.

In March 1985 the Aeronautical Policy Review Committee of the Office of Science and Technology Policy issued a report, *National Aeronautical R&D Goals: Technology for America's Future*. Three priorities were defined. First and foremost was advanced subsonic aircraft, then high-speed civil aircraft, and finally transatmospheric flight vehicles. In February 1987 a second report was issued by that group entitled *National Aeronautical R&D Goals: Agenda for Achievement*. It, too, emphasized the importance of advanced subsonic transports to both the national economy and the national transportation infrastructure. Page four of the second report describes as the leading priority in subsonics: "a new generation of superior U.S. aircraft." That section concludes with the warning, "We are approaching an important crossroad: one path leading to steady erosion of U.S. participation in world markets; the other to economic growth and job creation." The warning has gone unheeded.

  
Eugene E. Covert  
Chairman





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# **Aeronautical Technologies for the Twenty-First Century**





# EXECUTIVE SUMMARY

## INTRODUCTION

Throughout the latter half of this century the U.S. aeronautics industry has been one of the undisputed success stories in global competitiveness. From the end of World War II into the last decade, U.S. aircraft, engines, and parts have been among the leaders of, and in most cases have dominated, both the domestic and the foreign markets for subsonic transports, general aviation, commuter, and military aircraft. The buildup of the global transportation infrastructure (i.e., airports and air traffic management systems) has also been driven by U.S. technology and products. The aeronautics industry is the largest positive industrial contributor to the U.S. balance of trade, plays a vital role in maintaining the safety and convenience of air travel throughout the world, and provides important contributions to the defense of U.S. interests. Further, U.S. aircraft are flown in even the most remote parts of the world, engendering national pride and international prestige.

The importance that foreign governments ascribe to developing their domestic aeronautics industries is evidence of the perceived benefits from a strong aircraft industry. Europe and the Pacific rim countries have spawned numerous government and industry consortia aimed at producing aircraft and components across the entire range of the market. The European consortium, Airbus Industrie, has moved into second place in the market for commercial transport aircraft, while the emerging Taiwanese, Japanese, and Korean aircraft industries have begun to forge alliances with the two dominant U.S. companies, Boeing and McDonnell Douglas. Foreign interests dominate the commuter aircraft industry and are making inroads into the general aviation market. European and Far Eastern nations have begun to apply significant effort toward developing the technological base needed to compete even more effectively over the next several decades. The inference is obvious—**these nations believe it is in their national interest to maintain a healthy, broad-based domestic aircraft industry.**

In keeping with the charter of the National Aeronautics and Space Administration (NASA) to preserve "the role of the United States as a leader in aeronautical technology,"<sup>1</sup> NASA's Office of Aeronautics and Space Technology asked the Aeronautics and Space Engineering Board of the National Research Council to assist in assessing the current status of

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<sup>1</sup> National Aeronautics and Space Act, 1958.

aeronautics in the United States and to help identify the technology advances necessary to meet the challenges of the next several decades. The Aeronautics and Space Engineering Board established the Committee on Aeronautical Technologies, which defined an approach to helping NASA determine the appropriate level and focus of its near-term technology development efforts to maintain a leadership role in the years 2000–2020.

The Committee discussed the transportation infrastructure that would likely exist in 2020. From this, an estimate was made of the types and capabilities of aircraft required to compete in the global market in the 2000–2020 time frame. Based on these projections, the Committee identified the high-leverage technologies that offer the most significant advances in aeronautics to ensure long-term competitiveness for U.S. aircraft, engines, and components, and to enhance performance and safety in the total air transportation system.

## THE TECHNOLOGICAL CHALLENGE

The fact that U.S. market share in aeronautics is eroding is well documented and is discussed in detail throughout this report. The ultimate cause of eroding market share is that, for a variety of reasons, foreign competitors are able to market products that have lower total ownership costs than U.S. products.<sup>2</sup> This can be achieved, for example, through implementation of new technologies that reduce long-term operating costs, or through products that enter the market with significantly lower purchase price. This presents a challenge to the industry and to the U.S. government. U.S. aircraft, engine, and parts manufacturers must improve the quality, capability, and timeliness of their products, at reduced cost, to maintain or increase their market share.

Without advanced technology, market share will certainly be lost, but advanced technology cannot, by itself, ensure competitive products.

Foreign governments have undertaken determined, coordinated efforts to compete in all sectors of the market from general aviation through supersonic aircraft, and in most cases they have been successful. In terms of the current impact on the U.S. industry, this attack is most visible in the subsonic transport market that has historically been dominated by Boeing, Lockheed, and McDonnell Douglas. This segment of the market generates the highest revenues for aircraft, engine, and parts manufacturers.<sup>3</sup>

A long and successful history does not imply that there are no significant future gains to be realized. McDonnell Douglas and Boeing project a potential growth of 1 trillion passenger-miles each decade—to 2 trillion in the year 2000, and 4 trillion by 2020, most of which will be carried on advanced subsonic transport aircraft. Such estimates indicate that

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<sup>2</sup> Gellman Research Associates. 1990. *An Economic and Financial Review of Airbus Industrie*. Prepared for U.S. Department of Commerce International Trade Administration. Jenkintown, Pa.

<sup>3</sup> According to information published by the Aerospace Industries Association in 1991 (Aerospace Facts and Figures 91-92), subsonic transport aircraft accounted for \$27.64 billion in sales in 1990 (in then-year dollars), commuter aircraft accounted for \$2.81 billion, and aircraft engines (predominantly for subsonic transports) accounted for \$10.73 billion.

technical advances resulting in increased range and safety, and reduced fuel consumption, noise, and emissions can have significant effects on the competitive posture of the nation that produces them.

Although increased research into advanced subsonic aircraft technologies is needed to bring about a near-term competitive advantage, without continued resources applied to the environmental and economic viability of supersonic aircraft, U.S. participation in that important future market may be forfeited.

Similarly, advances in the technology of the global air traffic management (ATM) system can reduce congestion both in the air and on the ground, and make traveling by air safer and easier for everyone.

## NEEDS FOR THE FUTURE

The Committee identified seven needs that must be addressed by the U.S. aeronautics community, including NASA, the Federal Aviation Administration (FAA), aircraft manufacturers, and air carriers, if the United States is to maintain or increase its share of the global aircraft market: lower cost and greater convenience, greater capacity to handle passengers and cargo, reduced environmental impact, greater aircraft and ATM system safety, improved aircraft performance, more efficient technology transfer from NASA to industry, and reduced product development times. Neither the Committee's charter nor its makeup allowed detailed consideration of the latter two needs, so these are not discussed in detail in this report. The remaining five are discussed below in terms of the needs of industry and the nation.

1. Lower cost/greater convenience: Generally, people choose air travel over automobile, bus, ship, or rail because their desire for shorter trip times justifies the cost. Also, in many cases, air travel is the only choice, so that if the cost is excessive the potential traveler does not make the trip. To open new markets in developing nations and to expand current markets, the cost of the service must remain low enough to maintain that justification. Furthermore, the level of convenience of the service must not be compromised such that passengers in existing markets are driven to other forms of transportation. In short, advances in the speed, range, or payload of the various classes of aircraft must not be accompanied by large increases in cost or degradation of service. Thus, greater fuel efficiency and reduced operational costs must be vigorously pursued, and increases in airport and ATM system capacity must not come at the expense of convenience.

2. Greater capacity to handle passengers and cargo: A major factor that may impose a ceiling on the ability of the aviation industry to respond to the growing demand for air travel is airport and ATM system capacity. Where local restrictions allow, it is simplest to build more airports and runways. However, this is not possible in most cases. Rather, to open up new markets or to expand existing markets, it is imperative that both the ATM system and the existing airports be capable of dealing with more people and packages flying on more and different kinds of aircraft. Safe reductions in aircraft separation, better real-time weather reporting, and facilities for a wide variety of long- and short-range aircraft all contribute to the

ability to move more people and cargo through the system, and thus to the growth of both the industry and the economy.

3. Reduced environmental impact: The impact of aircraft on the environment is a limiting factor on the growth of the industry. Aircraft noise restrictions limit the proximity of airports to major population centers, the utility of rotorcraft within cities, and the potential for supersonic flight over land. In addition, a change in the ozone level that results from the emission of nitrogen oxide and hydrocarbons by aircraft is an area of growing concern that may, in the near future, limit the number and types of aircraft that fly over the United States and other environmentally conscious countries.

4. Greater aircraft/ATM system safety: As more planes take off and land each year, it is vital that the rate of accidents continues to decrease to avoid the perception that air travel is unsafe.

5. Improved aircraft performance: Advances in performance of conventional subsonic aircraft, rotorcraft, short takeoff and landing aircraft, and supersonic aircraft will enable more viable expansion into new markets and expansion of existing routes.

The Committee grouped advanced aircraft into three classes, within which recommendations were prepared that cut across specific technologies.

- advanced subsonic transport aircraft;
- high-speed civil transports (HSCTs), the next generation of supersonic transports; and
- short-haul aircraft (commuters, rotorcraft, and general aviation aircraft).

Similarly, the Committee identified five generic disciplines that encompass the technologies that will provide the greatest overall benefit toward meeting future needs: 1. aerodynamics, 2. propulsion, 3. materials and structures, 4. avionics and controls, and 5. cognitive engineering.<sup>4</sup> Table ES-1 relates these five disciplines to the five needs that were considered, and shows the primary benefits that will be gained from their development.

## THE NASA CIVIL AERONAUTICS PROGRAM

In the course of this study, there was much discussion on the respective roles of government, industry, and universities in developing, verifying, and applying technology. One conclusion emerged clearly: **without strong cooperation between commercial interests, universities, and government to define the technologies with the greatest potential payoff,**

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<sup>4</sup> Cognitive engineering is defined as the use of knowledge developed by the information, cognitive, and ergonomic sciences to enable more effective interactions among humans, vehicle systems, and ATM systems. Among other factors, it deals with how data are presented to an aircrew to produce effective information integration and decision making. In short, cognitive engineering uses knowledge about humans and technology to increase the effectiveness of the aircrew, flight controllers, and air transportation in general.

TABLE ES-1 Primary Benefits from Each Discipline

Need	Discipline	Primary Benefits
Lower cost/greater convenience	Avionics and control	More effective crew
	Cognitive engineering	Increased reliability
	Structures and materials	More effective crew
	Propulsion	Enhanced training
	Aerodynamics	Longer life/lower maintenance
Greater capacity	Avionics and controls	Global positioning (ground and air)
	Cognitive engineering	Real-time weather alerting
Reduced environmental impact	Propulsion	Optimized traffic management
	Aerodynamics	Optimized traffic management
Greater safety	Avionics and controls	Fewer emissions
	Cognitive engineering	Less noise
Improved performance	Propulsion	Less noise
	Aerodynamics	Lowered demands on crew
	Structures and materials	Fault-tolerant systems
	Avionics and controls	Reduced crew fatigue
		Enhanced teamwork/crew interactions

and to work in a concerted fashion toward their development, U.S. standing in aeronautics will continue to erode. The government cannot adequately address the needs of industry unless industry is involved in the process from the beginning. This does not imply that industry should guide government efforts, nor does it imply that the government should be involved in choosing which technologies are most appropriate for commercial application. The Committee believes that an approach is possible wherein government agencies, universities, and commercial entities work together to define and develop the appropriate technologies without jeopardizing the autonomy of basic research or the constraints of fair trade. A good example is the Energy Efficient Engine (E<sup>3</sup>) program that began in the late 1970s in response to the energy crisis. The E<sup>3</sup> program was a jointly funded, cooperative effort by NASA and the two largest U.S. engine

manufacturers, which established and met an aggressive goal for improved fuel economy. Much of the technology that is currently implemented in U.S. transport engines was a result of the E<sup>3</sup> program.

The need to form stronger alliances among all members of the aeronautics community, coupled with the importance aeronautics plays in the U.S. economy, has led the committee to identify four primary recommendations regarding NASA's future in aeronautics:

1. **NASA should emphasize the development of advanced aeronautical technologies in the following order: (1) advanced subsonic aircraft, (2) high-speed (supersonic) aircraft, and (3) short-haul aircraft.**

Advanced subsonic aircraft will continue to provide the bulk of the future market, even if a viable HSCT is developed. The Committee strongly believes technological advances in subsonic aircraft are possible that could provide U.S. industry with a major competitive edge. At the same time, the potential future market for HSCT is significant, and NASA should continue research on noise, sonic boom, and emissions, and should be on the forefront of the technology research and development required to bring about a technically and economically viable HSCT. In short, it is vital that an appropriate balance be struck between programs with immediate benefits to the nation and those that lay the groundwork for the future.

2. **NASA should work with aircraft manufacturers, the airline industry, and the FAA to bring about major improvements in the utility and safety of the global ATM system.**

Everyone who flies benefits from the safety and convenience of the ATM system, and it is in the national interest for U.S. technology to continue to lead the future development of the global system. Although the FAA is the lead agency in this area, NASA has much to contribute to a coordinated, national effort that includes ground, air, and space systems.

3. **NASA should commit to a greater level of technology validation to reduce the risk of incorporating advanced technology into U.S. products.**

Incorporation of new technology in production aircraft is risky. The major aircraft and engine manufacturers have significant aeronautics research and technology development capabilities, but they do not have the resources to engage in nonspecific, precompetitive research. Most major universities have facilities and talented people, but they are not equipped, staffed, or funded to perform the range and scope of validation that is required before industry can make effective use of a given technology. The FAA has capabilities to perform applied research, but its focus is regulatory in nature and not aimed at providing a competitive edge. Only NASA combines talent and experience in aeronautics research with a nationwide network of test facilities and research aircraft. Thus, NASA is the only organization in the United States with both the capability and the mandate to perform the basic research as well as the ground and

flight testing necessary to validate new concepts to the extent that they can begin to be incorporated into commercial aircraft. Although it is not NASA's role to be concerned with specific, product-oriented applications, to ensure a smooth transition of generic technologies into such applications, joint efforts among NASA, industry, and academia can improve the rate at which technology is validated for use.

#### **4. The magnitude of NASA's civil aeronautics budget should be increased.**

The attention paid to civil aeronautics in the NASA budget is not commensurate with the importance the industry plays in the nation's economy. This is particularly true, in the opinion of the Committee, when the NASA aeronautics budget is compared to its space research and development budget.<sup>5</sup> When new aircraft begin to enter service in the next century, whatever their configuration, the contribution to the U.S. economy from their manufacture and operation will continue to meet or exceed even the most significant contributions from space-related activities. Thus, the development of technologies to help make U.S. aeronautical products more competitive, and air travel safer and more convenient in the next century requires, and deserves, increased attention. Accordingly, **the Committee further recommends that the Office of Aeronautics and Space Technology (OAST) perform a review of its budget in light of the technologies discussed in this report and determine the level of funding appropriate to NASA's role in helping to offset the erosion of U.S. standing in the global market and to position the United States to capture future markets. OAST should report the results of its budget review to the NASA Administrator for review and consideration of the total program balance.** In most cases, the technologies recommended in this report represent areas in which NASA has existing programs. Where possible, the Committee has identified these existing programs and recommended that they be enhanced as appropriate. In some cases, however, the recommended technologies require new starts or restarts of old programs. The Committee has also attempted to identify proposed new programs wherever possible.

Tables ES-2 and ES-3 show the current (1992) NASA aeronautics budget (also see Chapter 1 and Appendix C). Chapter 1 of this report includes a discussion of the relative funding of each vehicle class and discipline shown in Tables ES-2 and ES-3. The Committee believes that the relative funding shown in Tables ES-2 and ES-3 is generally appropriate given the challenges identified in this report, with two exceptions. First, as mentioned above, the Committee believes that research into advanced subsonic aircraft should be emphasized relative to other classes of civilian aircraft. This is not currently the case. If the civilian portion of NASA's aeronautics budget is increased as the Committee has recommended, the portion devoted

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<sup>5</sup> According to information published by the Aerospace Industries Association in 1991 (Aerospace Facts and Figures 91-92), and the U.S. Commerce Department (Space Business Indicators, 1992) civil space sales accounted for approximately \$3.4 billion in 1990, while NASA devoted nearly \$5.1 billion to space-related research and development. Shipments of civil aircraft, engines, and parts accounted for more than \$33 billion in 1990, whereas the 1990 NASA budget devoted only \$0.889 billion (including research into military aircraft, construction of facilities, and research and operations support) to aeronautics research and development.

TABLE ES-2 NASA Research and Development Funding Mix (1992)

Category	1992 Research and Development Program Funding (millions of 1992 dollars, percent of total funding) <sup>a,b</sup>					
	Research and Technology Base <sup>c</sup>		Systems Technology Programs <sup>d</sup>		Total	
Advanced subsonic transport aircraft	48.6	8.5 %	44.9	7.8 %	93.5	16.3 %
High-speed civil transport	6.3	1.1 %	86.5	15.1 %	92.8	16.2 %
Short-haul aircraft	23.8	4.1 %	8.2	1.4 %	32.0	5.6 %
Critical disciplines <sup>e</sup>	140.6	24.5 %	62.4	10.9 %	203.0	35.4 %
Hypersonic/transatmos. technology <sup>f</sup>	30.2	5.3 %	—	—	30.2	5.3 %
High-performance aircraft <sup>g</sup>	111.6	19.4 %	11.1	1.9 %	122.7	21.3 %
<b>Total</b>	<b>361.1</b>	<b>62.8 %</b>	<b>213.1</b>	<b>37.2 %</b>	<b>574.2</b>	

Source: NASA Office of Aeronautics and Space Technology.

<sup>a</sup> Research and development funding only. Excludes wind tunnel refurbishment (\$62.8 million) and other construction of facilities funding (\$22.9 million), as well as research and operations support (\$210.1 million).

<sup>b</sup> Percentages are based on the total (\$574.2 million). Percentages may not add to 100% due to roundoff error.

<sup>c</sup> The research and technology base includes efforts in all aeronautical disciplines: aerodynamics; propulsion and power; materials and structures; controls, guidance, and human factors; systems analysis; and flight systems.

<sup>d</sup> Systems technology programs are technology and validation efforts aimed at specific vehicle or component applications.

<sup>e</sup> This category includes research and technology development in the traditional aeronautical disciplines that is not aimed at specific vehicle or component applications, or that applies to all vehicle classes.

<sup>f</sup> This category is primarily made up of the National Aerospace Plane Program (NASP).

<sup>g</sup> This category is made up of research that applies to high-performance military aircraft. NASA receives no funding from the Department of Defense for this research.



TABLE ES-3 1992 NASA Aeronautics Funding by Discipline.

Discipline	1992 Research and Development Funding (millions of 1992 dollars, percent of total funding) <sup>a,b</sup>						
	Advanced subsonic transport aircraft	High-speed civil transport	Short-haul aircraft	Critical disciplines <sup>c</sup>	Hypersonic/transatmos. technology <sup>d</sup>	High-performance aircraft <sup>e</sup>	Total
Aerodynamics	12.9 2.2%	2.1 0.4%	16.5 2.9%	93.6 16.3%	12.6 2.2%	33.9 5.9%	171.6 28.1%
Propulsion	16.8 2.9%	19.4 3.4%	3.0 0.5%	31.4 5.5%	11.6 2.0%	29.8 5.2%	112.0 19.5%
Materials and structures	28.1 4.9%	10.1 1.8%	3.3 0.6%	30.1 5.2%	3.1 0.5%	1.4 0.2%	76.1 13.3%
Controls, guidance, & human factors <sup>f</sup>	29.4 5.1%	0.7 0.1%	3.3 0.6%	25.8 4.5%	1.3 0.2%	3.9 0.7%	64.4 11.2%
Systems and operations <sup>g</sup>	2.3 0.4%	0.6 0.1%	5.9 1.0%	5.1 0.9%	1.6 0.3%	53.7 9.4%	69.2 12.1%
Environmental Compatibility	— —	59.9 10.4%	— —	— —	— —	— —	59.9 10.4%
Other <sup>h</sup>	4.0 0.7%	— —	— —	17.0 3.0%	— —	— —	21.0 3.7%
<b>Total</b>	<b>93.5 16.3%</b>	<b>92.8 16.2%</b>	<b>32.0 5.6%</b>	<b>203.0 35.4%</b>	<b>30.2 5.3%</b>	<b>122.7 21.4%</b>	<b>574.2</b>

Source: NASA Office of Aeronautics and Space Technology.

<sup>a</sup> Research and development funding only. Excludes wind tunnel refurbishment (\$62.8 million) and other construction of facilities funding (\$22.9 million), as well as research and operations support (\$210.1 million).

<sup>b</sup> Percentages are based on the total (\$574.2 million). Percentages may not add to 100% due to roundoff error.

<sup>c</sup> This category includes research and technology development in the traditional aeronautical disciplines that is not aimed at specific vehicle or component applications, or that applies to all vehicle classes.

<sup>d</sup> This category is primarily made up of the National Aerospace Plane Program (NASP).

<sup>e</sup> This category is made up of research that applies to high performance military aircraft. NASA receives no funding from the Department of defense for this research.

<sup>f</sup> This category includes the disciplines identified in this report as avionics and controls, and cognitive engineering.

<sup>g</sup> The category includes both flight systems research and systems analysis studies.

<sup>h</sup> The advanced subsonic transport category includes \$4 million for aging aircraft, and the critical disciplines category includes \$17 million for high-performance computing.

to advanced subsonic transport aircraft should garner a substantial fraction of that increase in comparison with other vehicle classes. If the NASA budget remains at current levels, the Committee believes that resources should be shifted from areas that are less vital to the nation's economy into technology development for aeronautics, particularly for advanced subsonic transport aircraft. Second, the Committee believes that NASA's current emphasis on rotorcraft in the short-haul category should be balanced with additional funding for general aviation and commuter aircraft or, if new sources of funding cannot be found, there should be a reallocation of resources from rotorcraft to conventional short-haul aircraft. Although the Committee was not asked to address the source of additional funding or reallocation of existing funding, it cannot be ignored that reallocation of military or space-related resources may be an option for increasing civil aeronautics' funding if sources outside of NASA cannot be found. This, however, is a matter for NASA and policy makers within the government to determine.

## **AIRCRAFT OF THE FUTURE**

The following discussion summarizes issues that are treated in detail in the body of the report. The recommendations are labeled "general" and "specific" to distinguish between those that pertain to the overall direction of research and technology development and those that relate to specific programs. The specific recommendations pertain to existing programs that the Committee believes should be enhanced and new efforts that should be undertaken. The recommendations are listed in order of importance.

### **Advanced Subsonic Aircraft**

The following recommendations pertain to NASA's approach to developing technology and its potential interactions with industry to ensure that the proper technologies are advanced.

#### **General Recommendation:**

**NASA should increase its investments in research and technology development to support future subsonic transports to reflect the importance of this segment of the market.**

#### **Specific Recommendation:**

- 1. NASA should plan and execute a major technology development and validation activity for advanced subsonic transports that is more extensive than that proposed for the HSCT program. This should include**
  - improvements in operational performance of subsonic transport aircraft; and**

- complementary, cohesive, long-term cooperation with academia and industry.<sup>6</sup>

### **High-Speed Civil Transports**

Although the potential market for HSCT appears to be significant, there are scientific and technological barriers to the development of an economically viable HSCT. These technical barriers include the need to better understand the effects of engine emissions on atmospheric phenomena and the level of sonic boom that can be tolerated over populated areas, if such a level exists. Once these issues are better understood, engineering solutions must be developed to meet the associated restrictions. The concept of an HSCT is technically viable—the supersonic transport (SST), which was developed by the British and French in the 1970s and continues to fly a regular schedule, is evidence of that. However, although the SST is a technological success, it is an economic failure. Due, in part, to the fact that, more than 20 years after the SST was first seriously proposed, the sonic boom generated precludes it from operating over populated land areas. Furthermore, in the last decade it has become increasingly clear that the ozone-depleting emissions from a fleet of supersonic transports could do significant damage to the environment, thus precluding wide-scale operation of a U.S. HSCT. In short, the Committee believes the issues of sonic boom generation over land and ozone depletion must be adequately addressed before a major design and development effort is undertaken for an HSCT. This leads to the following recommendations:

#### **General Recommendation:**

**NASA should be the primary contributor to technologies that identify and reduce the environmental impact of HSCT, including ozone depletion, airport noise and emissions, and sonic boom.**

#### **Specific Recommendations:**

1. **NASA should enhance its atmospheric research program to determine whether acceptable levels of ozone-depleting emissions from HSCT exist. If they exist, NASA should perform the necessary propulsion research and validation to meet those levels.**
2. **NASA should continue its work toward advances in HSCT propulsion technology that reduce noxious emissions and engine noise.**

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<sup>6</sup> According to NASA's Office of Aeronautics and Space Technology, the current proposed funding for Phase 2 of the High-Speed Research (HSR-2) program is \$1.233 billion over the years 1994-2000. This funding level includes \$549 million for airframe-related technology, \$569 million for propulsion technology, and \$115 million for flight-deck systems.

3. The HSCT program should be tailored to ensure that propulsion, aerodynamics, structures and materials, and overall vehicle management and control technologies are adequately represented.
4. Although industry is not currently planning HSCT supersonic flights over populated areas, NASA should continue an aggressive program to define acceptable sonic boom levels and should continue its program to investigate approaches to meeting those levels.

### **Short-Haul Aircraft**

Given the projected increase in congestion at hub airports, commuter aircraft and rotorcraft will be used increasingly over the next several decades, and the market that bypasses major hubs is likely to expand. Furthermore, a significantly enhanced ATM system will likely reduce the difficulty in obtaining and maintaining the skills needed for a private pilot's license, which will spark an increase in general aviation traffic over the next several decades. In other words, short-haul aircraft will continue to be an indispensable segment of the market and so deserve adequate attention.

The following recommendations pertain to NASA's efforts to incorporate short-haul aircraft into its overall aeronautics program:

#### **General Recommendation:**

NASA should enlarge its support of the key technologies for general aviation, commuter aircraft, and rotorcraft through extensive validation, and should both sponsor and participate in comprehensive system studies to define total aircraft systems, with investigations into their technical and economic characteristics. This should include a more equal balance between rotorcraft and conventional short-haul aircraft.

#### **Specific Recommendations:**

1. NASA should undertake an aggressive safety research program focused on cognitive engineering and the features that are unique to the operation of commuter, rotorcraft, and general aviation aircraft.
2. NASA's unique capabilities in simulation and training should be focused toward enhancing the initial training and skill maintenance programs of all aircraft pilots and mechanics.
3. NASA's extensive capabilities in aerodynamics, structures, and acoustics should be applied toward major improvements in rotorcraft economics, speed, and efficiency.
4. NASA and the FAA should undertake a study to establish the degree to which existing airport capacity could be increased by shifting some short-haul traffic

to helicopters and tiltrotors, using vertiports integrated into available airport real estate.

5. NASA should undertake an extensive research and technology development effort to improve rotorcraft passenger comfort.

## **ENVIRONMENTAL AND OPERATIONAL ISSUES**

Environmental and operational issues relate to all classes of aircraft and encompass each of the generic disciplines. NASA has a significant role to play in determining acceptable limits for the environmental impact of aircraft, defining approaches for their safe and cost-effective operation, and developing appropriate technologies.

### **Environmental Issues**

The future operation of all aircraft classes will be increasingly constrained by a complex system of national and international restrictions on both noise and emissions. Without significant effort to make U.S. aircraft less intrusive, substantial competitive advantage may be forfeited. The following recommendations address the issues involved in reducing the environmental impact of aircraft in an effort to focus NASA's ongoing noise and atmospheric research programs.

#### **General Recommendation:**

NASA, the U.S. aircraft industry, and the FAA must work together to address national and international environmental concerns both to help the United States gain a competitive edge and to avoid increasing the adverse environmental effects of aircraft on the ground and in flight.

#### **Specific Recommendations:**

1. Current and proposed research programs sponsored by NASA should be continued to enhance understanding of the impact of engine emissions on atmospheric ozone.
  - It is imperative that improved modeling, data collection, and verification of models of the chemistry and dynamics of the troposphere also be included in NASA's long-term subsonic aircraft program.
  - NASA is strongly encouraged to investigate worst-case scenarios for stratospheric ozone depletion to establish a basis for reasonable regulation aircraft emissions and to begin developing engineering solutions.

- To enable a successful commercial HSCT fleet, NASA must continue or accelerate its current programs in advanced emission reduction technology related to the chemistry and dynamics of the stratosphere.
- 2. NASA's aggressive research and development program for aircraft noise reduction must include HSCT jet engine noise suppression, subsonic engine fan noise suppression, airframe noise reduction, and noise abatement flight operations.
- 3. NASA should continue its research and development program in sonic boom reduction for HSCT.

### **Operational Issues**

There are increasingly serious constraints on the movement of all classes of aircraft at many U.S. airports, and the condition is as bad, or worse, in Europe and the Far East. The problem lies in the limited capacity of airports to accommodate aircraft on the ground, the limited capacity of the air traffic management system to accommodate aircraft in the air, and the difficulties in integrating the two. Unfortunately, opportunities to expand existing facilities will be severely limited in the future. Thus, the best hope for addressing the problem of congestion over the long-term is through the application of advanced technology to develop new airport and air traffic management systems. The following recommendations address the issues of capacity and congestion as they relate to airport systems and to current and future ATM systems.

#### **General Recommendation:**

Coordinated activity should be undertaken between NASA and the FAA to significantly increase the capacity of the worldwide aviation system, beginning with the U.S. domestic ATM system.

#### **Specific Recommendations:**

1. NASA should increase its current cooperative effort with the FAA, the airlines, and aircraft manufacturers to bring about implementation of the Global Positioning System (GPS) for use in the ATM system as soon as possible.
2. NASA should focus its efforts, in cooperation with the FAA and industry, to expedite
  - full integration of on-board communication, navigation, and flight management systems;

- control and standardization of software for both on-board and ground-based computer systems;
- development of a mission monitor to address any unacceptable developments that occur on board the aircraft, in the satellite system, or in the communication system, whether in flight or on the ground;
- development of a satellite communication system along with a global infrastructure to ensure clear and redundant communications; and
- refinement of inertial navigational systems, including the use of fiber optics.

## **AERONAUTICAL DISCIPLINES**

The generic disciplines are discussed below. The Committee believes that some discussion of the emerging field of integrated design is also warranted. The increasing maturity of computational approaches in various disciplines provides new opportunities to couple the disciplines early in the design process. Routinely treating aerodynamics, structures, propulsion, and controls virtually simultaneously and continuously throughout each step of the design has large payoffs. Although the Committee has no specific recommendations in this area, it hopes that continued attention will be paid throughout the community to enhancing the scope and utility of integrated design techniques.

The following sections discuss the key technological concepts in each discipline and present recommendations for focusing NASA's efforts in the near-term to ensure long-term results.

### **Aerodynamics**

The aerodynamics discipline encompasses a wide range of analytical and computational technologies, as well as design and test facilities. NASA, and the National Advisory Committee for Aeronautics before it, traditionally served as the focal point for civilian aerodynamics research and validation in the United States. Such a focus is needed if the United States is to remain at the forefront of research in aerodynamics. The following recommendations reflect the Committee's concerns about the level of technology validation that is performed in this discipline and include several specific areas in which NASA should enhance its capabilities.

#### **General Recommendation:**

**NASA must continue to provide the necessary resources for aerodynamics research and validation, including resources focused on specific key technologies, resources to maintain and enhance ground and flight test facilities, and resources for enhanced analytical and design capabilities.**

**Specific Recommendations:**

The following research topics are of vital importance to NASA's research effort in aerodynamics. (The order of importance is strongly dependent upon industrial marketing decisions in the next decade.)

1. aerodynamic cruise performance, including subsonic and supersonic laminar flow control technology;
2. aircraft propulsion/airframe integration for both subsonic and supersonic aircraft;
3. low speed and high lift for subsonic configurations, including wake mechanics, wake vortex, and measurement technology;
4. computational fluid dynamics for aircraft design, including validation of codes;
5. low speed and high lift for supersonic configurations; and
6. aerodynamics of rotorcraft.

In order of importance, the following should be the focus of a program to enhance NASA's ground-based experimental facilities:

1. revitalization of existing facilities on an expedited basis;
2. establishment of an intensive program to develop high-resolution nonintrusive instrumentation;
3. fitting of the 40'  $\times$  80' tunnel at the Ames Research Center with acoustic lining;
4. development of a low-speed (Mach 0.1–0.5), low-disturbance test capability to operate at chord Reynolds numbers in excess of 50 million; and
5. research to examine the feasibility of a supersonic (Mach 2–6) low disturbance test capability to operate at full-chord Reynolds numbers of 400 million to 500 million.

In order of importance, the following should be the focus of a program to enhance NASA's experimental flight facilities:

1. revitalization of flight research capability and in-flight technology validation efforts in all speed regimes; and
2. development of advanced measurement technologies for flight research.



**Propulsion**

Propulsion technology offers the greatest single contribution to improvement of the cruising economy of aircraft and to lessening their environmental impact. The past three generations of gas turbine engines, for example, have seen increased turbine inlet temperatures, increased compressor pressure ratio, increased bypass ratio, and improved fan and nacelle performance, all leading to greater thrust-to-weight ratios, reduced fuel consumption, reduced noise and emissions, and improved reliability. The following recommendations reflect the Committee's belief that this rapid pace can be maintained over the next two decades, thus providing superior propulsion systems well into the next century.

**General Recommendation:**

**NASA must vastly strengthen its current propulsion technology program to include:**

- much greater emphasis on subsonic transport propulsion systems where the United States has lost its technological edge over foreign competitors;
- continued support for the HSCT propulsion program; and
- a strong, broad-based propulsion technology program to position the United States for the post-2000 short-haul markets, including a better balance between vertical takeoff and landing commuter systems and conventional systems.

**Specific Recommendations:**

1. NASA should increase its support for generic computational and experimental propulsion research. In addition, NASA must lead in the development of technical communication with industry in computational science applied to propulsion.
2. NASA should take the initiative in setting up a joint NASA/industry program for innovative subsonic propulsion technology that is at least equivalent to the NASA/industry HSCT propulsion program.
3. NASA must increase its support for the development of specialty materials not currently available as commodities that, if properly developed, will become common in aircraft engines.
4. The basic research effort at the Lewis Research Center (LeRC) in low nitric oxide combustors for the HSCT has produced excellent results and the momentum should be maintained. NASA should put in place the planned Joint Technology Acquisition Program between LeRC and industry.
5. NASA should take advantage of its unique position to mount a substantial program in active control technologies for aircraft engines.

6. **NASA's turbomachinery research program, should be strengthened to the point at which NASA can recapture its leadership role.**
7. **NASA's LeRC should direct increased effort toward the enabling technologies in compressor, combustor/turbine, and control accessories for engines appropriate to short-haul aircraft.**

### **Materials and Structures**

Structural weight is the single largest item in the empty weight of an aircraft and is, therefore, a major factor in the original acquisition and operating costs. The durability of the materials used affects both maintenance costs and useful lifetime of the aircraft. Advanced materials and innovative structural design concepts hold the promise of reducing overall structural weight while maintaining strength, stiffness, and durability.

NASA has a long history in developing innovative structural and materials concepts that have found wide application in both commercial and military aircraft. However, it takes a great deal of time to build the experience base that is needed to establish confidence in new materials and structural concepts. On one hand, commercial interests are unlikely to aggressively pursue the incorporation of new structures into their airframes or engines until this confidence has been built but, on the other hand, they lack the time and resources required to build that base of operational experience. Thus, in its development of new materials and structural concepts, NASA must include extensive testing aimed at building confidence in them to a level at which industry can begin to incorporate them without undue risk.

### **General Recommendation:**

**NASA's structures and materials program should emphasize continuing fundamental research to achieve both evolutionary and revolutionary advances in materials and structures, as well as focused technology programs in materials and structures to address specific aircraft system requirements. This should include:**

- **a major role in establishing the data base that is required for realistic materials- and structures-related regulations;**
- **a significant increase in NASA's investment in the technology of shaping, forming, and fastening; and**
- **a lead role in stimulating innovative structural design and manufacturing research for both airframes and engines in a program conducted jointly with industry.**

**Specific Recommendations:**

1. **The highest priority in NASA's long-range engine materials research program should be on ceramic matrix composite developments including fabrication technology, although intermetallics should continue to be an active part of engine materials research for the longer term, with emphasis on improving damage tolerance.**
2. **NASA's existing program of basic research in materials and structures should improve understanding of failure modes in composites, increase damage tolerance, and introduce advanced means of nondestructive evaluation.**
3. **Automated sensing and feedback control should be an increasing part of NASA's research program, capitalizing on "smart structures" advances.**
4. **The introduction of metal matrix composites into high-pressure compressor disks deserves major emphasis in NASA's engine programs for the nearer term.**
5. **NASA's program of materials and structures research for the HSCT should give high priority to developing basic composite materials, advanced metallic systems, and design concepts and processing techniques for 225–375°F operations.**

**Avionics and Controls**

The 1980s saw a significant change in the nature of commercial air transportation and military aircraft operations as a consequence of remarkable growth in application of new avionics. These innovations provided increased functional capability without adverse impact on the weight of aircraft. However, advances in avionics have brought a new set of problems including inadequate testing and validation to ensure that such systems meet all requirements when they are introduced, and the often massive cost and schedule overruns resulting from software development and validation problems. Further, demand has increased for coordination and standardization in areas as diverse as microwave landing systems, software standards, electromagnetic vulnerability standards, and certification and testing requirements.

Current research and development in avionics and controls is expected to result in operational solutions to many of the problems anticipated because of air traffic growth. Techniques for more effective use of computer automation to manage air traffic are being developed, but integration of that technology into the national and worldwide system is a major challenge. A primary hope for meeting the challenge of increasing congestion in the air and on the ground is full-scale implementation of the GPS. Emerging technologies also offer significant enhancement of the pilot's situational awareness, which is fundamental to improved safety and mission effectiveness.

NASA has a great deal of expertise in developing and validating advanced avionics and control concepts for spacecraft. Where appropriate, NASA should be aggressive in

incorporating these concepts into research aircraft and simulator systems, in close relationship with the FAA and industry, with the goal of building an adequate experience base. The following recommendations reflect this belief.

#### **General Recommendation:**

**NASA should play a major role in the development and validation of the key technologies in avionics and control, including system development and integration, simulator and/or experimental flight validation, and serving in a technical advisory capacity for industry and other agencies of the government.**

#### **Specific Recommendations:**

1. **NASA should enhance its current efforts, in conjunction with the FAA, academia, and industry, to produce advances in:**
  - **flight path management;**
  - **pilot/vehicle interface (i.e., establish a cognitive engineering effort in this area);**
  - **avionics and controls integration;**
  - **control function applications; and**
  - **aircraft power and actuation.**

#### **Cognitive Engineering**

For the next two to three decades the information sciences and human factors disciplines will play a different and more fundamental part in aeronautics than in the past. As the power of computers increases, the next step is to allow the aircrew to do what people do best and use the computer to support these activities and carry out whatever other tasks are necessary. This human-centered approach involves multidisciplinary engineering activities and is represented in this report by the term "cognitive engineering," to express the synergy between the traditional disciplines of information sciences and human factors.

The recommendations for this discipline relate to two specific goals: improvement of the overall ATM system (capacity and operations) and enhancement of safety. NASA has a wide range of expertise in cognitive engineering as related to both aircraft and space systems, but NASA's current programs should be enhanced and focused to produce real improvements in flight systems. Application of this expertise to future systems, both on board aircraft and in ground systems, will lead to safer, more convenient air travel in the next century.

**General Recommendation:**

**NASA should expand its efforts to conduct broad-based, interdisciplinary research into the causes, nature, and alleviation of human error, with specific reference to airborne and ATM environments.**

- **The most promising theories and experiments should be pursued as part of a continuing, long-range effort aimed at accident reduction.**
- **NASA should lead in the development and validation of training and operational strategy and tactics that are intrinsically tolerant to situations demanding divided attention operations by the individual or crew.**
- **NASA should work with the FAA and industry to address the total human/system concepts and develop methods to ensure valid and reliable system operations.**

**Specific Recommendations:**

1. **NASA should conduct research to develop and demonstrate techniques to improve the pilot's situational awareness and spatial orientation.**
2. **In addition to its work with the National Incident Reporting System, NASA should work with the FAA and the National Transportation Safety Board to analyze all available data on aircraft accidents and incidents to determine the history and trend of human errors, contributing factors, type of equipment involved, and other relevant matters.**
3. **NASA's current research in error alleviation should be expanded to include:**
  - **systems that can detect developing critical situations, independent of the crews's alertness, and inform and assist the crew regarding appropriate corrective measures;**
  - **concepts, methods, criteria, and the technology for error-tolerant system design; and**
  - **development of prototype, "massively smart" interfaces, both in the simulator and in the air.**
4. **NASA, with FAA involvement, should extend its investigations of highly reliable avionics to total system concepts applicable to ATM automation.**
5. **NASA should continue its research into four-dimensional guidance algorithms and simulation techniques for ATM.**



**PART I:**  
**OVERVIEW**

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## OVERVIEW OF THE STUDY

### INTRODUCTION

In keeping with the charter of the National Aeronautics and Space Administration (NASA) to preserve "the role of the United States as a leader in aeronautical technology . . .,"<sup>1</sup> NASA's Office of Aeronautics and Space Technology asked the Aeronautics and Space Engineering Board of the National Research Council to assist in assessing the current status of aeronautical technology and to help define a long-term aeronautics technology program to meet the challenges of the next several decades. The Aeronautics and Space Engineering Board established an ad hoc steering committee that defined a three-part approach to helping NASA determine the appropriate level and focus its near-term technology development efforts so as to produce a competitive level of capability in the years 2000-2020.

The first phase of the study was designed to review the transportation infrastructure and forecast the types of aircraft, and their capabilities, that are likely to exist in the global market in the 2000-2020 time frame. The Committee estimated the growth that can be expected in domestic and international markets, and forecast the generic advances in performance that will be required to meet that growth.

The Committee concluded that the development of technology for advanced subsonic transport aircraft is vital to the future of the U.S. aeronautics industry. The short-haul category, consisting of aircraft that carry fewer than 100 passengers, is important but is a much smaller market in terms of both revenue and employment. Supersonic transport aircraft may also play an important role in the long-term, but at this stage, important technical questions must be answered concerning atmospheric effects, noise, sonic boom, and overall economic viability. This is not to imply that NASA's work on future, exotic concepts should be eliminated, rather, it is important that a proper balance be struck between making plans to shape the future and addressing issues of immediate importance—without which the future is in jeopardy.

The second phase of the study used the aircraft system forecasts to identify high-leverage technologies both in the traditional disciplines of aeronautics (aerodynamics, propulsion,

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<sup>1</sup> National Aeronautics and Space Act of 1958.

structures, and avionics) and in areas of technology that have only recently been integrated into any but the most sophisticated systems (for example, cognitive engineering). The technical panels of the Committee then identified the technologies that offer the most significant advances that could contribute to economic competitiveness and improvement of the air transportation system.

The third phase of the study addressed, very briefly, the issue of the interaction between government (primarily NASA) and the U.S. aircraft industry in the development of aeronautical technology. The U.S. and global aircraft markets have changed in the last decade from being totally dominated by U.S. manufacturers to the current condition in which foreign competition has seized a significant share of the market. This erosion of standing the market is due, in some measure, to a perceived failure of the U.S. aeronautical technology community to develop or adopt technologies that ultimately result in better products. This portion of the study investigated the possibilities for a more effective relationship between all members of the community.

The report is divided into three parts. Part I provides background on the benefits and economics of the aircraft industry. Part II is a system-by-system analysis of the current status, outlook, and barriers to progress in the various types of aircraft under study, including NASA's contributions. Part III deals with technological and operational issues across the various system types. Each of the following chapters (chapters 2-11) of the report includes key findings of the Committee and specific recommendations to NASA pertaining to the particular subject of that chapter. Findings and recommendations include discussion of the role of government, where appropriate (particularly those sections designating NASA's contributions).

The remaining sections of this overview chapter discuss the benefits of a strong aeronautics industry and the role that technological advancement plays in keeping that industry competitive. These are also touched on in later sections but are offered here as a necessary background to understanding the total U.S. aeronautics program.

## **MAINTAINING A STRONG AERONAUTICS PROGRAM**

The fact that the U.S. aeronautics industry is a vital part of the U.S. economy is undeniable. However, the overall benefits of the industry to the country as a whole are not often articulated in a manner that focuses attention on what must be done to meet future challenges. The definition of a strong aeronautics program must include a healthy and vigorous research effort, and a similarly aggressive drive to get the fruits of that research into products that meet the needs of the marketplace. The result of such an action should be that U.S. airframe, engine, and aircraft components and parts manufacturers maintain or increase their share of the global market as that market expands into new services and new parts of the world.

What are the overall benefits of a strong U.S. presence in the aeronautics industry, and what must be done to maintain that presence? The most fundamental benefit is the contribution that the aircraft industry makes to the quality of life of the people of the United States through the economic benefits and jobs generated by a healthy, competitive, and growing industry.

Air travel contributes to the ability to do business in all sectors of the economy, through greater mobility of workers and the corresponding ability to integrate geographically separate divisions of companies, including expansion into foreign markets. Furthermore, air travel has made it possible for people to live and work in areas of the country determined by the availability of employment, without compromising family ties or vacation options. Thus, the quality of the air transportation system has a direct impact on the quality of life of every U.S. citizen. The increasing demands for business and personal travel have created corresponding demands for more and safer air transportation that connects more places with greater overall convenience. These demands are manifested in the requirements that airlines levy on aircraft manufacturers, on the air traffic management (ATM) system, and on airport services. Moreover, the presence of a healthy aircraft industry, and a healthy technological base in aeronautics and related disciplines, allows the United States to build world-class military aircraft, engenders national prestige around the world, and benefits the economy as a whole through growth and balance of trade. Thus, it matters a great deal that this nation has the technology and manufacturing capability required to build the best military and civilian aircraft in the world.

### Economic Indicators in Air Transportation

The size of the worldwide air transportation market in which U.S. companies competed in 1990 is impressive: more than 1 trillion revenue passenger-miles and 45 billion revenue ton-miles of freight and mail annually. Forecasts for growth into the next century are even more striking: a doubling of revenue passenger-miles by 2005 and as many as 4 trillion revenue passenger-miles by 2020, a growth in revenue ton-miles to more than 200 billion by 2020, and a growth in the jet fleet to 14,000 by 2005 and 20,000 by 2020.<sup>2</sup>

The market is huge, and more important, it is growing.<sup>3</sup> In the past, growth in the air transport market would have automatically meant a corresponding growth in the U.S. aircraft industry, since U.S. companies dominated the market. In recent years, however, foreign competitors have made significant inroads into the design and manufacturing dominance of U.S. companies, to the point where the short-haul and general aviation segments of the market have been almost totally lost. Airbus Industrie (a European consortium) has supplanted McDonnell Douglas as the second largest maker of large commercial subsonic aircraft. Clearly, as the worldwide market grows, U.S. companies will be forced to compete more effectively than in the past to realize the benefits of that growth.

Does it matter that opportunities to maintain dominance in the industry might be lost? As long as the U.S. industry maintains a constant level of sales, or a slight growth, will a failure to maximize the advantage of the growing market mean a net decrease in the standard of living of the citizens of the United States? The answer to each question is yes. Every year more

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<sup>2</sup> Boeing Commercial Airplane Group. 1990. Current Market Outlook—World Travel Market Demand and Airplane Supply Requirements. Seattle, Wash.

<sup>3</sup> Aerospace Industries Association of America. 1991. Aerospace Facts and Figures 91-92. Washington, D.C.

workers enter the job market than leave it. Each year a greater percentage of women enter the job market, and overseas citizens continue to seek employment in the United States because of its high standard of living. Maintenance of this standard of living requires creation of new jobs through expansion of existing industries or creation of new industries.

An important economic measure is market share—the percentage of the market captured by a company's, or a country's, products. On a gross level, revenues are a function of market share and the rate of growth of the industry. It is possible to lose market share and yet maintain revenues if the industry is growing, and it is possible to maintain or even increase revenues in a stagnant or shrinking market by increasing market share. It is important that in a rapidly growing market, U.S. manufacturers maintain the capability to keep pace with increasing orders. If U.S. manufacturers cannot keep pace, orders will increasingly fall to foreign competitors.

### **Benefits of Large Market Share**

The benefits to a nation of a large market share are threefold: security of the jobs and tax base that the industry produces influence on the pace and direction of the market and the national prestige that follows products into the world market. In considering the U.S. aeronautics industry, in particular, the first benefit is clear—more high-quality jobs for U.S. workers, more capital within the industry for reinvestment, greater profits to U.S. shareholders, and an increased tax base that filters through the entire U.S. economy. A loss in market share can reduce revenues, reduce the potential to grow along with the industry as a whole and, thus, reduce the ability of manufacturers to provide jobs over the long term. This affects not only the aircraft industry proper, but also its numerous supporting and benefiting industries and, thus, the economy as a whole.

The second benefit, U.S. influence in the marketplace, enables U.S. manufacturers to determine the opportunities that provide the greatest payoff for their efforts and to exploit them at a pace consistent with U.S. interests. When U.S. market share is high, U.S. manufacturers have the luxury of time and capital to develop additional capabilities, to better pick and choose opportunities, and to attract and retain high-quality personnel. As U.S. market share declines, however, the market is likely to be driven increasingly by foreign competitors. Thus, U.S. manufacturers will be less able to provide stable employment because their control over market forces will be significantly decreased. Although the expanding market may offset the effects of decreasing market share over the short term, continued erosion in market share ultimately will produce a corresponding erosion in the heretofore undisputed dominance of the market that the United States has enjoyed. Additional revenues that might have been gained will not be realized, and foreign competitors will wield greater and greater influence on market forces.

The third benefit relates to how the perception of a nation's standing in the world affects its ability to lead politically, militarily, and economically. This perception is strongly tied to the standing of the nation's products in the world's economy. In short, the ability to develop and market a wide range of world-class products engenders a belief that the producing country belongs in the upper echelon of the world's nations. Given that the technological sophistication of foreign competitors equals that of U.S. aircraft manufacturers in some areas, and given the

primary importance that foreign governments ascribe to the global aeronautics industry, the United States must take steps to keep pace. Although the United States has a sizable lead in industry sales, much effort is needed to maintain that lead throughout the next several decades and beyond.

A growing industry implies penetration of civilian aircraft sales into new markets as well as an increase in the size of current markets. Penetration into new markets can be accomplished with conventional aircraft as more airports are built in developing areas of the world. Penetration may also be accomplished via expanded capability of vertical takeoff and landing or short takeoff and landing aircraft in areas where air travel is profitable but where conventional airports are difficult to build. U.S. companies must provide for these needs ahead of the foreign competition so that as the global industry grows, the U.S. portion of the industry will grow rather than decline. The key to maintaining economic growth and market share in the aircraft industry is the same as in all other highly competitive markets: customer satisfaction. It is vital that U.S. industry, in partnership with the universities and government agencies that develop the latest technological concepts, address a broad range of issues that ultimately relate to making better products.

Mechanisms that allow greater use of new technologies in products and that permit manufacturers to shorten the time required to make those products, clearly allow manufacturers to offer more sophisticated aircraft to all users. Better performance, whether improved fuel economy, greater range, more passengers, or reduced maintenance requirements, also provides a clear incentive to buy American aircraft. Similarly, improved safety, reduced cost, and greater capacity to move passengers and cargo in a convenient manner all contribute to the competitiveness of U.S. products. Finally, given the increased awareness of the impact that aircraft have on the global environment, and the expectation that more strict limits on noise and engine emissions will be set as population densities and numbers of aircraft increase around the world, it is clear that efforts to make aircraft less intrusive, while maintaining all other advances in safety and performance, will yield more competitive products.

## REQUIREMENTS FOR GROWTH

Realization of the benefits described above requires that the technology that forms the basis of the aeronautics industry be focused on the primary missions of the industry—competitive products and services. NASA has played and will continue to play a key role in development of this technology. The Committee has identified seven needs that must be addressed by the U.S. aeronautics community, including NASA, the Federal Aviation Administration (FAA), aircraft manufacturers, and air carriers, if the United States is to maintain or increase its share of the global aircraft market: (1) improved aircraft performance, (2) greater capacity to handle passengers and cargo, (3) lower cost and greater convenience, (4) greater aircraft and ATM system safety, (5) reduced environmental impact, (6) more efficient technology transfer from NASA to industry, and (7) reduced product development times. Neither the Committee's charter nor its makeup allowed detailed consideration of the last two needs, so they are not discussed in detail in this report.

1. Lower cost/greater convenience: Generally, people choose air travel over automobile, bus, ship, or rail because their desire for shorter trip times justifies the cost. Also, in many cases, air travel is the only choice, so that if the cost is excessive the potential traveler does not make the trip. To open new markets in developing nations and to expand current markets, the cost of the service must remain low enough to maintain that justification. Furthermore, the level of convenience of the service must not be compromised such that passengers in existing markets are driven to other forms of transportation. In short, advances in the speed, range, or payload of the various classes of aircraft must not be accompanied by large increases in cost or degradation of service. Thus, greater fuel efficiency and reduced operational costs must be vigorously pursued, and increases in airport and ATM system capacity must not come at the expense of convenience.

2. Greater capacity to handle passengers and cargo: A major factor that may impose a ceiling on the ability of the aviation industry to respond to the growing demand for air travel is airport and ATM system capacity. Where local restrictions allow, it is simplest to build more airports and runways. However, this is not possible in most cases. Rather, to open up new markets or to expand existing markets, it is imperative that both the ATM system and the existing airports be capable of dealing with more people and packages flying on more and different kinds of aircraft. Safe reductions in aircraft separation, better real-time weather reporting, and facilities for a wide variety of long- and short-range aircraft all contribute to the ability to move more people and cargo through the system, and thus to the growth of both the industry and the economy.

3. Reduced environmental impact: The impact of aircraft on the environment is a limiting factor on the growth of the industry. Aircraft noise restrictions limit the proximity of airports to major population centers, the utility of rotorcraft within cities, and the potential for supersonic flight over land. In addition, a change in the ozone level that results from the emission of nitrogen oxide and hydrocarbons by aircraft is an area of growing concern that may, in the near future, limit the number and types of aircraft that fly over the United States and other environmentally conscious countries.

4. Greater aircraft/ATM system safety: As more planes take off and land each year, it is vital that the rate of accidents continues to decrease to avoid the perception that air travel is unsafe.

5. Improved aircraft performance: Advances in performance of conventional subsonic aircraft, rotorcraft, short takeoff and landing aircraft, and supersonic aircraft will enable more viable expansion into new markets and expansion of existing routes.

Two additional areas of need have been identified by the Committee but have not been addressed in detail: (1) better technology transfer and (2) shortened product development times. The belief is prevalent in the industry today that although the United States leads the world in understanding the basic technology of flight systems, U.S. companies are slow to incorporate useful new technology into their products. This delay is due partly to the difficulty in obtaining access to advanced technology, but also to the risk involved in developing products based on unproven technologies. Foreign competitors have reached a level of sophistication that allows

them to produce aircraft that are technically equal to those produced in the United States, in part because they are often shielded from the associated risk through government/industry cooperative arrangements. The potential impact on U.S. market share is immense; airlines will buy the aircraft that reduces their cost, or increases their capability, with little regard to its country of origin. If a foreign competitor produces an aircraft that is superior to one offered by a U.S. company, or is equivalent but lower in price, U.S. market share will be lost along with the jobs and tax base that go with it.

In a similar vein, it is not enough to make a superior product if the product does not also arrive in the marketplace ahead of the competition. As with the incorporation of new technology, there is a concern in the industry that U.S. companies are at a disadvantage in meeting rapid changes in market demand because of an inability to integrate design, supply, and manufacturing. More specialized aircraft, shorter production runs, and special-purpose modifications are likely to gain in importance in the future. The ability to go from identification of a market need to production of a product ahead of the competition will be essential for maintaining U.S. market share. These two weaknesses are difficult to quantify, but the Committee believes that they are important to the competitive posture of the nation's aircraft industry.

All these needs, and particularly the two that were not specifically addressed by the Committee, have managerial and financial, as well as technological, components. In fact, in some cases the importance of technology pales in comparison to the impact that can be gained from reduced cost, reduced liability, more creative investment and tax policies, and more creative management. Nonetheless, the Committee feels that the technological advances that enable better commercial products are necessary (if not sufficient) for maintaining the health of the U.S. aircraft industry.

## THE ROLE OF TECHNOLOGY

The Committee was asked to address the technologies that will be necessary to meet the needs of the next several decades. What are the technologies that will allow U.S. companies to increase the performance of their aircraft? What technologies can contribute to decreasing airport congestion without affecting safety and convenience? How can the undesirable environmental impact of aircraft be lessened, and the favorable impacts nurtured, without making the cost of operations prohibitive? The Committee identified the following five generic disciplines for use in consideration of these questions and established subcommittees to address each area in detail: (1) propulsion, (2) aerodynamics, (3) materials and structures, (4) avionics and controls, and (5) cognitive engineering.<sup>4</sup> In addition, a subcommittee was established to

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<sup>4</sup> Cognitive engineering is defined as the use of knowledge developed by the cognitive sciences to allow the human/machine interface to become more effective. Among other factors, it deals with how data are presented to an aircrew to produce effective information integration and decision making. In short, cognitive engineering uses knowledge about humans and technology to increase the effectiveness of the aircrew, flight controllers, and air transportation in general.

address operational and environmental issues. Although not independent disciplines per se, the Committee considered operational and environmental issues to be of such importance that they warrant specific attention.

Another area that many members of the Committee felt was worthy of close consideration is manufacturing technology and, in general, those technologies that contribute to shortening the product development cycle and reducing manufacturing cost. However, the Committee was not constituted to consider these technologies in detail, nor does it consider development of commercial manufacturing processes to be the province of NASA. Nonetheless, the Committee believes that advances in the individual technologies that make up a complete commercial manufacturing process are vital to the long-term health of the aircraft industry and that NASA, in partnership with industry, has a role to play in their development.

Table 1-1 relates the five disciplines that have been considered by the Committee to the first five needs (i.e., excluding technology transfer and speed to market) discussed in the previous section, in terms of the benefits the disciplines offer.

The needs that are listed in Table 1-1 are not necessarily independent; they overlap and often complement, or conflict with, each other. Congestion, for example, can be reduced at the expense of safety—unless advanced ATM systems are put in place to ensure adequate margins. Reducing noise may tend to increase operating costs, reduced emissions may degrade performance. In short, advances in one technology may help meet a number of needs or may necessitate additional advances in a complementary technology. The implication, of course, is that development of advanced technology cannot be undertaken without some thought to its application and its relationship to other development efforts. It is also important that a realistic appraisal be made of the cost of the technology versus its long- and short-term benefits. To reach the potential of each individual technology, an orchestrated approach must be used that raises the level of technology over the entire spectrum. This includes improvements in the quality of the basic components that make up current aircraft, as well as more exotic systems that will enable the development of future aircraft. Advances in aerodynamics, for example, although useful in themselves, lose some of their impact without corresponding advances in the structures, materials, and control systems that make up a complete aircraft.

The issue then is, how can the United States ensure that its technology development efforts—however they might be distributed among government, universities, and industry—work together to produce advances that pass the tests of the marketplace? It is the belief of the Committee that government organizations such as NASA must not have sole responsibility for choosing which technologies should be developed to meet market demands. Those choices are best left to commercial enterprises. Commercial entities, on the other hand, should not be required to stake their continued existence, and the jobs and taxes that they produce, on their ability to develop and demonstrate high-risk technologies by themselves. Only government has the resources to assume that risk.

The simplistic belief is that there exists a point along the continuum of technology development at which government involvement should end and industrial involvement should begin. Unfortunately, such a clean interface is rarely, if ever, available. More typically, government develops technology to a point at which it believes the technology is validated or



TABLE 1-1 Primary Benefits from Each Discipline

Need	Discipline	Primary Benefits
<b>Lower cost/greater convenience</b>	Avionics and control	More effective crew Increased reliability
	Cognitive engineering	More effective crew Enhanced training
	Structures and materials	Longer life/lower maintenance
	Propulsion	Lower fuel costs/reduced maintenance/higher reliability
	Aerodynamics	Lower fuel costs
<b>Greater capacity</b>	Avionics and controls	Global positioning (ground and air) Real-time weather alerting Optimized traffic management
	Cognitive engineering	Optimized traffic management
<b>Reduced environmental impact</b>	Propulsion	Fewer emissions Less noise
	Aerodynamics	Less noise
<b>Greater safety</b>	Avionics and controls	Lowered demands on crew Fault-tolerant systems
	Cognitive engineering	Reduced crew fatigue Enhanced teamwork/crew interactions Optimized human/machine interactions
<b>Improved performance</b>	Propulsion	Greater range and speed (reduced fuel consumption)
	Aerodynamics	Greater range and speed (increased lift/drag ratio)
	Structures and materials	Greater range and speed (lower weight)
	Avionics and controls	Increased reliability

can no longer justify the cost, but short of what industry considers adequate validation with acceptable risk for commercial development. Thus, technology that might aid in meeting the needs of the nation is often wasted because it remains unvalidated. The Committee believes that closing this gap will prove to be a major challenge over the next several decades and that, without some mechanism by which a smooth transition of technology can be effected, the potential represented by the technologies discussed in this report will never be fully met.

## THE CURRENT NASA AERONAUTICS PROGRAM

The current NASA program for aeronautics can be described most efficiently in terms of the funding that is applied to the various vehicle classes and technical disciplines. Tables 1-2 and 1-3 (and Appendix C) show how NASA's aeronautics research and development program was structured in 1992.<sup>5</sup> NASA describes its program in terms of four vehicle categories:

1. "Subsonic aircraft," which includes both the advanced subsonic transport aircraft and the short-haul categories discussed in this report, as well as efforts to enhance the safety and productivity of the air traffic management system;
2. "High-speed aircraft," which corresponds to the HSCT category in this report;
3. "High-performance aircraft," which is strictly devoted to research into military aircraft; and
4. "Hypersonic/transatmospheric aircraft," which is almost exclusively devoted to the National Aerospace Plane (NASP) program.

For purposes of clarity and consistency, Tables 1-2 and 1-3 separate the NASA "subsonic aircraft" category into two categories, advanced subsonic transport aircraft and short-haul aircraft.

In addition, NASA identifies a fifth category, called "critical disciplines," that encompasses research and technology development efforts in the traditional aeronautical disciplines that are not aimed at a specific vehicle class. The critical disciplines category includes very basic scientific investigations, the applications for which have yet to be identified, as well as activities that are farther along in the development process but are deemed to have application to several vehicle classes.

As seen in Table 1-2 the critical disciplines category is the single largest item in the research and development funding for aeronautics, making up approximately 35 percent of the total \$574.2 million in 1992. In other words, approximately one-third of the program is devoted to non-specific research, while the remaining two-thirds is devoted to research with specific vehicle or component applications. Since generic research, such as that represented by the critical disciplines category, benefits all classes of aircraft, it is difficult to critique its level of

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<sup>5</sup> Excludes wind tunnel refurbishment (\$62.8 million) and other construction of facilities funding (\$22.9 million), as well as research and operations support (\$210.1 million).

TABLE 1-2 1992 NASA Aeronautics Program Funding

Category	1992 Research and Development Program Funding (millions of 1992 dollars, percent of total funding) <sup>a,b</sup>			
	Research and Technology Base <sup>c</sup>		Systems Technology Programs <sup>d</sup>	
				Total
Advanced subsonic transport aircraft	48.6	8.5%	44.9	93.5 16.3%
High-speed civil transport	6.3	1.1%	86.5	92.8 16.2%
Short-haul aircraft	23.8	4.1%	8.2	32.0 5.6%
Critical disciplines <sup>e</sup>	140.6	24.5%	62.4	203.0 35.4%
Hypersonic/transatmos. technology <sup>f</sup>	30.2	5.3%	—	30.2 5.3%
High-performance aircraft <sup>g</sup>	111.6	19.4%	11.1	122.7 21.3%
<b>Total</b>	<b>361.1</b>	<b>62.8%</b>	<b>213.1</b>	<b>574.2</b>

Source: NASA Office of Aeronautics and Space Technology.

<sup>a</sup> Research and development funding only. Excludes wind tunnel refurbishment (\$62.8 million) and other construction of facilities funding (\$22.9 million), as well as research and operations support (\$210.1 million).

<sup>b</sup> Percentages are based on the total (\$574.2 million). Percentages may not add to 100% due to roundoff error.

<sup>c</sup> The research and technology base includes efforts in all aeronautical disciplines: aerodynamics; propulsion and power; materials and structures; controls, guidance, and human factors; systems analysis; and flight systems.

<sup>d</sup> Systems technology programs are technology and validation efforts aimed at specific vehicle or component applications.

<sup>e</sup> This category includes research and technology development in the traditional aeronautical disciplines that is not aimed at specific vehicle or component applications, or that applies to all vehicle classes.

<sup>f</sup> This category is primarily made up of the National Aerospace Plane Program (NASP).

<sup>g</sup> This category is made up of research that applies to high-performance military aircraft. NASA receives no funding from the Department of Defense for this research.

funding or the relative mix between specific disciplines. However, it is important that NASA guard against this generic research being inadvertently skewed toward more exotic technologies that will disproportionately benefit HSCT, the National Aerospace Plane Program, or military aircraft, to the detriment of advanced subsonic transport and short-haul aircraft. Such research is very much a part of NASA's charter, but it should not be unduly influenced by the perception that subsonic flight, for example, is a "mature field," or that short-haul aircraft are less worthy of fundamental investigation than high-speed or high-performance applications. In the long run both the subsonic and short-haul aircraft will need NASA support if the United States is to remain competitive in these markets.

NASA has identified two additional categories which cut across the vehicle and critical disciplines categories. The "research and technology base" includes research in the traditional aeronautical disciplines that has not reached a level at which it can be inserted into a particular component or vehicle design and test program. "Systems technology programs" encompass efforts to validate technology through actual design and test programs, but also include less advanced technology development efforts that merit very focused attention. An example of this latter case is the first phase of the High-Speed Research program (HSR-1), which at \$76.4 million makes up the bulk of the HSCT category. The HSR-1 program includes very basic research into the atmospheric effects of supersonic aircraft, and investigations into reducing the effects of sonic boom, and yet was included in the systems technology programs category along with more advanced technology validation programs in military, advanced subsonic, and short-haul aircraft. Similarly, the \$62.4 million that was devoted to high-performance computing and the Numerical Aerodynamics Simulation program was placed in the systems technology programs category. It is important that the systems technology programs category, which made up approximately 37 percent of the total program in 1992, not be interpreted as representing NASA's efforts in technology validation. The actual amount of effort devoted to technology validation through vehicle and component design and testing is actually much less than 37 percent of the program.

Research into high-performance military aircraft was the second largest item in the 1992 research and technology budget, exceeding both advanced subsonic transport aircraft research and HSCT. It is part of the NASA charter to help maintain military aeronautics at a superior level, and so it is entirely appropriate for NASA to be engaged in this type of research even though NASA receives no funding from the Department of Defense for this program. It was not in the Committee's charter to consider either military aeronautical technologies or the relative importance of military and civilian applications, and thus no evaluation has been made of the appropriateness of this category or the technologies it encompasses. It is worth mentioning, however, that as the nation reevaluates its priorities based on recent changes in the world's political situation, NASA's military aircraft budget may be one source of additional manpower and funding to meet the economic challenges that have, in some cases, supplanted military ones.

Table 1-3 shows how the 1992 research and development budget for aeronautics was distributed by discipline. The disciplines shown in Table 1-3 correspond to those discussed in Chapters 5-11 of this report, although avionics and controls (Chapter 10) and cognitive

TABLE 1-3 1992 NASA Aeronautics Funding by Discipline.

Discipline	1992 Research and Development Funding (millions of 1992 dollars, percent of total funding) <sup>a,b</sup>					
	Advanced subsonic transport aircraft	High-speed civil transport	Short-haul aircraft	Critical disciplines <sup>c</sup>	Hypersonic/transatmos. technology <sup>d</sup>	High-performance aircraft <sup>e</sup>
Aerodynamics	12.9 2.2%	2.1 0.4%	16.5 2.9%	93.6 16.3%	12.6 2.2%	33.9 5.9%
Propulsion	16.8 2.9%	19.4 3.4%	3.0 0.5%	31.4 5.5%	11.6 2.0%	29.8 5.2%
Materials and structures	28.1 4.9%	10.1 1.8%	3.3 0.6%	30.1 5.2%	3.1 0.5%	1.4 0.2%
Controls, guidance, & human factors <sup>f</sup>	29.4 5.1%	0.7 0.1%	3.3 0.6%	25.8 4.5%	1.3 0.2%	3.9 0.7%
Systems and operations <sup>g</sup>	2.3 0.4%	0.6 0.1%	5.9 1.0%	5.1 0.9%	1.6 0.3%	53.7 9.4%
Environmental Compatibility	— —	59.9 10.4%	— —	— —	— —	— —
Other <sup>h</sup>	4.0 0.7%	— —	— —	17.0 3.0%	— —	— —
<b>Total</b>	<b>93.5 16.3%</b>	<b>92.8 16.2%</b>	<b>32.0 5.6%</b>	<b>203.0 35.4%</b>	<b>30.2 5.3%</b>	<b>122.7 21.4%</b>
						<b>574.2</b>

Source: NASA Office of Aeronautics and Space Technology.

<sup>a</sup> Research and development funding only. Excludes wind tunnel refurbishment (\$62.8 million) and other construction of facilities funding (\$22.9 million), as well as research and operations support (\$210.1 million).

<sup>b</sup> Percentages are based on the total (\$574.2 million).

<sup>c</sup> This category includes research and technology development in the traditional aeronautical disciplines that is not aimed at specific vehicle or component applications, or that applies to all vehicle classes.

<sup>d</sup> This category is primarily made up of the National Aerospace Plane Program (NASP).

<sup>e</sup> This category is made up of research that applies to high performance military aircraft. NASA receives no funding from the Department of defense for this research.

<sup>f</sup> This category includes the disciplines identified in this report as avionics and controls, and cognitive engineering.

<sup>g</sup> The category includes both flight systems research and systems analysis studies.

<sup>h</sup> The advanced subsonic transport category includes \$4 million for aging aircraft, and the critical disciplines category includes \$17 million for high-performance computing.

engineering (Chapter 11) are combined in the single discipline called "controls, guidance, and human factors." While it was not within the scope of the Committee's activities to recommend specific funding levels for the various parts of the program, or for the program as a whole, it is the Committee's belief that, in general, the relative funding between disciplines is appropriate given the primary technical challenges facing aircraft designers. The one exception is the short-haul category, which is heavily weighted towards rotorcraft (Appendix C). Although the Committee recognizes that short-haul aircraft, particularly general aviation, is of somewhat lower priority than the other classes of civilian aircraft, a more balanced short-haul program could be of great benefit to U.S. industry. Within the HSCT category the funding is dominated by environmental compatibility (\$59.9 million) and, to a lesser extent, by propulsion (\$19.4 million) and materials and structures (\$10.1 million). Given that the primary barrier to a successful HSCT is its environmental compatibility, this is appropriate. Similarly, within the advanced subsonic transport class, the funding is distributed evenly between disciplines, concentrating slightly on advanced materials and controls technologies. This also seems appropriate given the broad range of technologies that are likely to contribute to the success of future subsonic transport aircraft.

As stated in several places throughout this report the Committee believes that advanced subsonic aircraft research and technology should be emphasized over other classes of aircraft. According to the information in Tables 1-2 and 1-3, this is not currently the case. One should not attribute too much importance to this funding profile—it changes from year to year as programs begin and end, and the relative mix will certainly vary to account for changing national priorities.

The Committee believes that the overall NASA civil aeronautics budget should be increased to reflect the importance of the industry to the nation. Without recommending a specific magnitude of increase, it is clear that to carry out the technologies recommended in the following chapters will require both new programs and expansions of existing programs. Where possible, the Committee has pointed out instances in which NASA has existing programs that meet the identified needs. The Committee believes, however, that NASA is best qualified to define a specific funding profile that meets the needs identified in this report and that is based on budgetary realities. Such an effort should take into account the capabilities and plans of other government agencies, particularly the FAA.

Identifying the source of additional funding is also outside the Committee's charter. It cannot be ignored, however, that the potential for increasing aeronautics spending is limited. Reallocation of military aeronautics spending to increase the civilian portion is one possibility, as is reallocating space research and technology funds to aeronautics. Outside the current NASA budget the prospects are just as limited, if not more so. Nonetheless, it is the opinion of the Committee that NASA technology can make a significant contribution in helping U.S. industry remain competitive in sales of aircraft, engines, and parts. How that is brought about is a matter for NASA and the policy makers within government to determine.

**PART II:**  
**STATUS AND OUTLOOK**  
**BY INDUSTRY SEGMENT**





## SUBSONIC TRANSPORT AIRCRAFT

### INTRODUCTION

Although U.S. advanced subsonic transport aircraft continue to surpass all foreign competition in total sales, U.S. market share has been declining significantly. This chapter describes the current market for large subsonic aircraft and projects how the market is expected to change over the next several decades. The White House Office of Science and Technology Policy's Aeronautical Policy Review Committee issued a report in 1985 that emphasized advanced subsonic aircraft over both supersonic and transatmospheric aircraft partly because subsonic technology can generate the resources needed to exploit ensuing opportunities in supersonic and transatmospheric flight.<sup>1</sup> *It is the opinion of the Committee that this same order of emphasis should be met and maintained in current programs and into the next century.* The technologies that are needed to enable the United States to compete effectively in the advanced subsonic transport market are discussed and recommendations are given regarding the role of the National Aeronautics and Space Administration (NASA) in furthering those technologies. The boxed material summarizes the primary recommendations discussed in this chapter and the benefits to be gained from research and technology aimed at advanced subsonic transport aircraft.

In the current (1992) aeronautics budget, NASA devoted \$93.5 million to research and technology efforts aimed specifically at advanced subsonic transport aircraft. Also, as described in Chapter 1, some portion of NASA's basic technology effort, called "critical disciplines," will contribute to this vehicle class as well. This level of funding is of the same order as that currently devoted to High-Speed Civil Transport (HSCT) research, which is primarily intended to investigate environmental concerns. As the nation's priorities are reevaluated in light of the recent changes in the world situation and the growing importance of economic competition, the emphasis placed by the Europeans on the importance of technology development to support

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<sup>1</sup> Executive Office of the President. 1985. National Aeronautical R&D Goals: Technology for America's Future. Report of the Aeronautical Policy Review Committee, Office of Science and Technology Policy. Washington, D.C.

subsonic aircraft, and the importance of subsonic transport aircraft to the global market, it stands to reason that this level of funding should increase, both as part of an overall increase in the NASA aeronautics budget, and in relation to other categories of aircraft.

## CURRENT INDUSTRY STATUS

As noted earlier, the world air transportation system in which U.S. products compete (excluding Eastern Europe and the former Soviet Union) flew more than 1 trillion revenue passenger-miles in 1990, and traffic is expected to approximately double each decade. Although sales of U.S.-produced transport aircraft totaled \$27 billion in 1990 (then-year dollars) and grew to almost \$35 billion in 1991 (then-year dollars),<sup>2</sup> the share of the global market captured by U.S. producers, based on orders for transport aircraft, declined from 87 percent in 1980 to 64 percent in 1989.<sup>3</sup> By 1990 the United Kingdom, Germany, and France had invested approximately \$26 billion in the Airbus Industrie consortium for research, development, certification, production, and price support of the A-300 family of aircraft. To date, the A-300, A-310, A-320, A-330, and A-340 series has captured approximately a quarter of the world market and moved Airbus Industrie to a position in the industry ahead of McDonnell Douglas and second only to Boeing. Airbus Industrie forecasts that by 2006 it will have captured 35 percent of the market.<sup>4</sup> Furthermore, Pacific rim countries—Japan, Taiwan, and Korea—have begun to devote significant resources as well and can be expected to increase their involvement in the market accordingly.

The technology of subsonic transports has progressed enormously since the introduction of the first jet transports in the late 1950s. Major improvements have been effected in safety, navigation, thrust management, aircraft control, flight path control, engine noise, engine emissions, and all-weather operation. Also, fuel burned per aircraft seat has decreased dramatically over the last 30 years. For example, in the long-range cruise mode, fuel consumption has decreased by more than 64 percent for aircraft having design ranges less than 4,000 miles (Figure 2-1)<sup>5</sup> and by more than 55 percent for aircraft with design ranges greater than 4,000 miles (Figure 2-2). This is significant because a decrease in fuel costs, either through lower prices or greater efficiency, relates directly to an operator's bottom line. In 1990, U.S. air carriers consumed 14.9 billion gallons of jet fuel at a cost of nearly \$11.5 billion. Although this fuel cost represented, on average, only 17.6 percent of operating expenses, even

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<sup>2</sup> Aerospace Industries Association of America. 1991. *Aerospace Industries Association 1991 Year-end Review and Forecast*. Washington D.C.

<sup>3</sup> Gellman Research Associates. 1990. *An Economic and Financial Review of Airbus Industrie*. Prepared for U.S. Department of Commerce International Trade Administration. Jenkintown, Pa.

<sup>4</sup> The Aerospace Research Center for the Aerospace Industries Association of America. 1991. *The U.S. Aerospace Industry in the 1990s — A Global Perspective*. Washington D.C.

<sup>5</sup> Illustrations in this chapter are based on data provided by the Boeing Commercial Airplane Group and the McDonnell Douglas Aircraft Company.

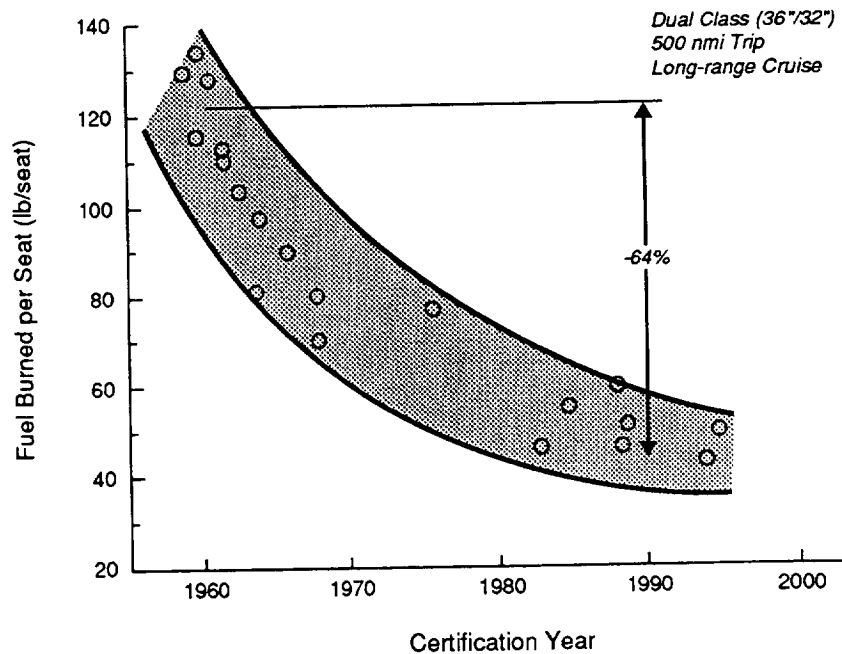


FIGURE 2-1 Fuel burn comparison for short- and medium-range airplanes (design range  $\leq 4,000$  nautical miles).

a relatively small reduction (e.g., 1 percent) would result in more than \$100 million reduction in operating costs.

The significant increases in performance realized in the past have been due, in part, to increasing size (economy of scale) and, in part, to improvements in virtually all disciplines that support the design, manufacture, and operation of aircraft. Dramatic improvements in reliability and ease of operations have led, in many cases, to two-man cockpit crews, with a resultant decrease in operating costs.

Although aircraft prices are increasing, based on cost per pound of empty operating weight (shown in Figure 2-3), direct operating costs (as shown in Figure 2-4) have remained approximately constant because of the offsetting effects of reductions in fuel burned. Approximately half of the airlines' direct operating costs are ownership costs (acquisition and interest), even if fuel prices double, as shown in Table 2-1. The data in this figure are averages for three classes of aircraft, the 737-400, the 757-500, and the 747-400, operating over ranges of 500, 1,000, and 2,000 nautical miles, respectively.

In interpreting the numbers in Table 2-1, it should be kept in mind that net profit is a percentage based on the difference between two large numbers. Thus, the percent impact on the direct operating cost (DOC) may have considerable leverage with respect to profit. The net profit (defined as the difference between revenues and cost, divided by revenues) is about 5 percent for a well-managed airline. Thus, for example, a 4.7 percent increase in DOC due to a 25 percent increase in fuel costs would virtually erase the 5 percent profit. Conversely, a 25 percent reduction in fuel costs, through either lower prices or greater efficiency, that produces

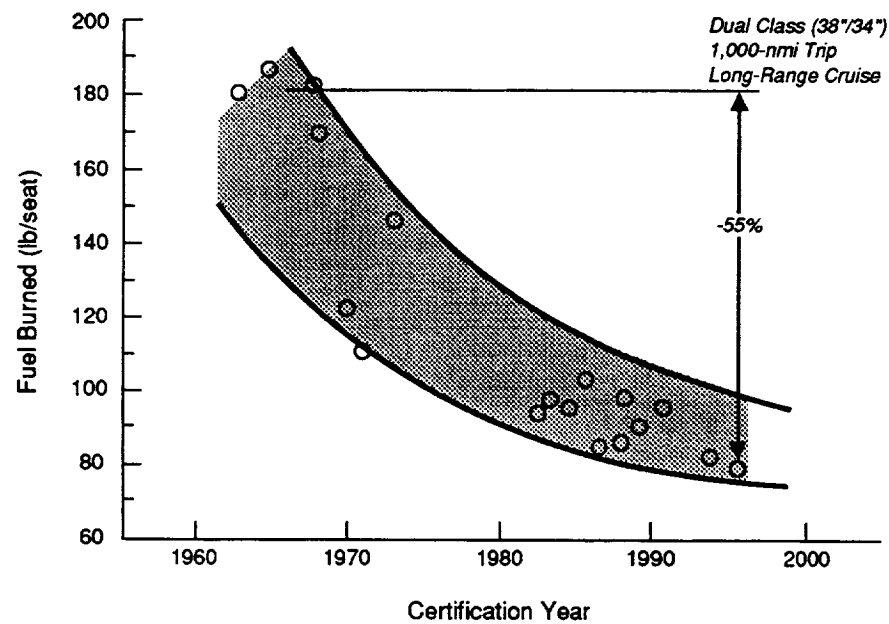


FIGURE 2-2 Fuel burn comparison for long-range aircraft (design range  $\geq 4,000$  nautical miles).

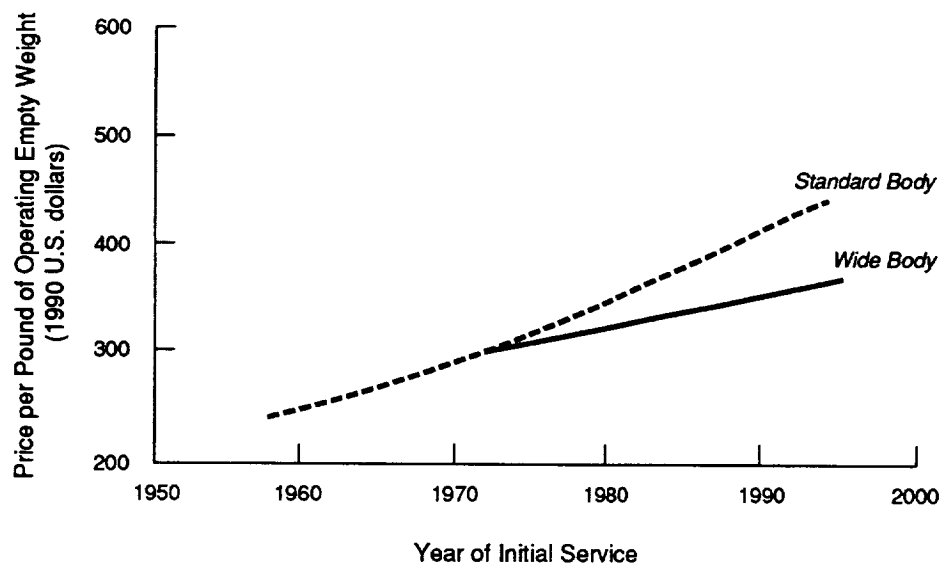


FIGURE 2-3 Airplane price trends.

a 4.7 percent decrease in DOC would nearly double the net profit. This fact shows the leverage attributable to improved efficiency resulting from advanced technology.

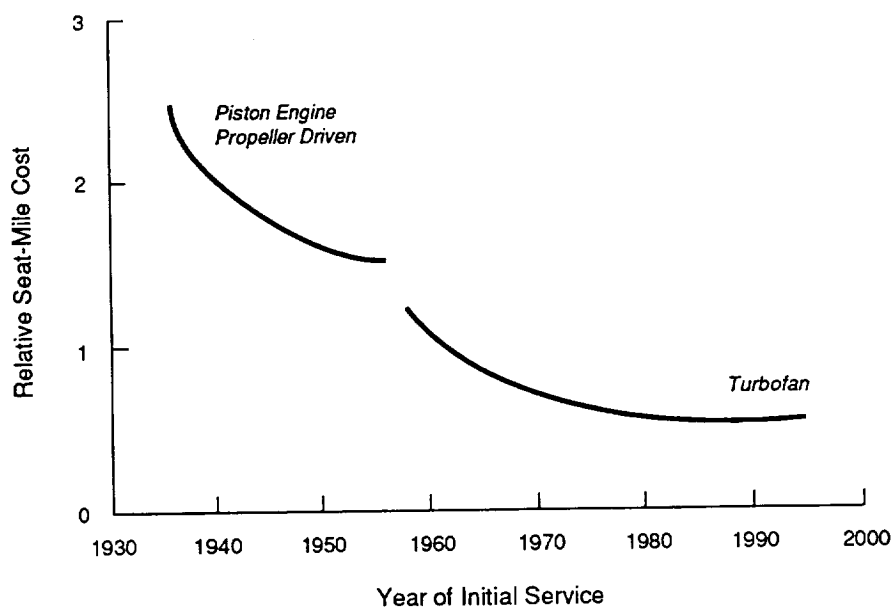


FIGURE 2-4 Direct operating cost trends.

TABLE 2-1 Direct Operating Cost (DOC) — Major Drivers

	\$0.63 Fuel (1990 Level)		\$1.20 Fuel	
	DOC BREAKDOWN (%)	IMPACT ON DOC OF 25% CHANGE (%)	DOC BREAKDOWN (%)	IMPACT ON DOC OF 25% CHANGE (%)
Crew	13.3	3.3	11.4	2.9
Maintenance	14.4	3.6	12.3	3.1
Insurance	1.5	0.4	1.3	0.3
Fuel	18.6	4.7	30.3	7.6
Ownership	52.2	13.1	44.7	11.2

## MARKET FORECAST

The air transportation system is growing. Industry and government forecasts project an increase of about a trillion revenue passengers each decade—to 2 trillion in the year 2000, 3 trillion in 2010, and 4 trillion in 2020. The McDonnell Douglas Aircraft Company forecasts the possibility of still greater growth (Figure 2-5).

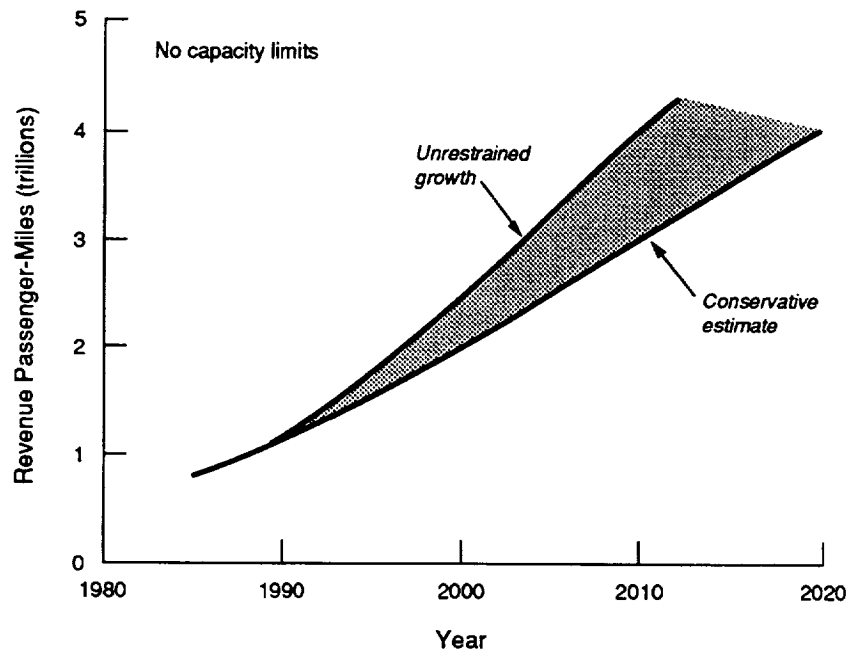


FIGURE 2-5 Projected world passenger traffic.

Even if constrained by limitations of airports and airways or by a lower level of growth than forecast, revenue passenger-miles are very likely to at least double over the next three decades. By far the largest part of the current and projected air traffic is flown by the subsonic jet transport fleet. In Figure 2-6, the estimated portions of the conservative forecasts of Figure 2-5 are flown by commuter turboprops with passenger capacities less than 100, the subsonic fleet with passenger capacities greater than 100, and a potentially successful high-speed civil transport (HSCT) in the year 2020.

There are now 9,000 jet transports in the international commercial fleet; by 2005 this figure is forecast to be 14,000; and in 2020, 19,500 subsonic jet transports if there is an HSCT, 21,000 if there is not.

The market for new transports consists of replacing old or obsolete aircraft and satisfying requirements for growth. The forecast market for 1991 to 2005 is for 9,000 transport aircraft worth \$600 billion in sales in 1990 dollars. The follow-on market to the year 2020 will be comparable—more than a trillion dollars in three decades. The international market for transport aeronautical products vastly exceeds that for any other category of U.S. manufactured goods.

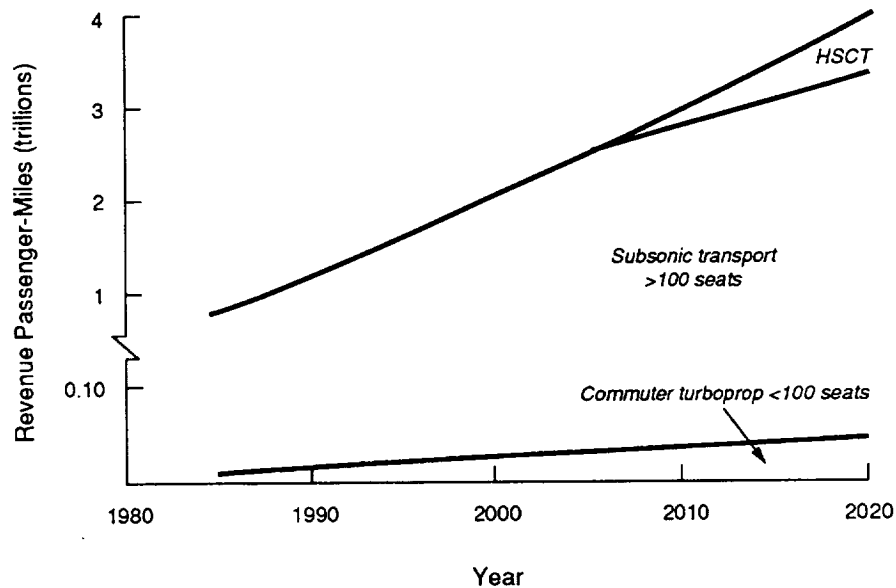


FIGURE 2-6 Potential traffic distribution.

Currently there are also more than 5,000 turboprop aircraft in service with passenger capacities of less than 100. In the forecast period, this class of service will grow. Though modest in terms of revenue passenger-miles and total sales compared to large subsonic transports, this class of aircraft comprises a large total of the departures and contributes significantly to the congestion problem (Figure 2-7). Aircraft other than turboprops may emerge

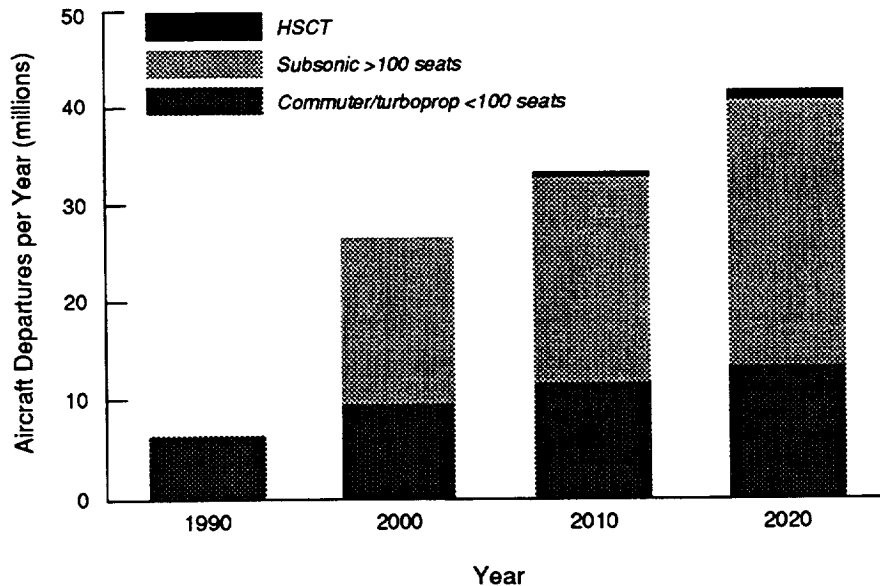


FIGURE 2-7 Projected worldwide aircraft departures.

for commuter use and some portion will move into the greater-than-100 passenger class, as represented by the middle portion of Figure 2-7.

Transport aircraft used by commercial airlines can be broadly categorized by their seating capacity and their range capability. The solid elliptical-shaped areas in Figure 2-8 depict classes

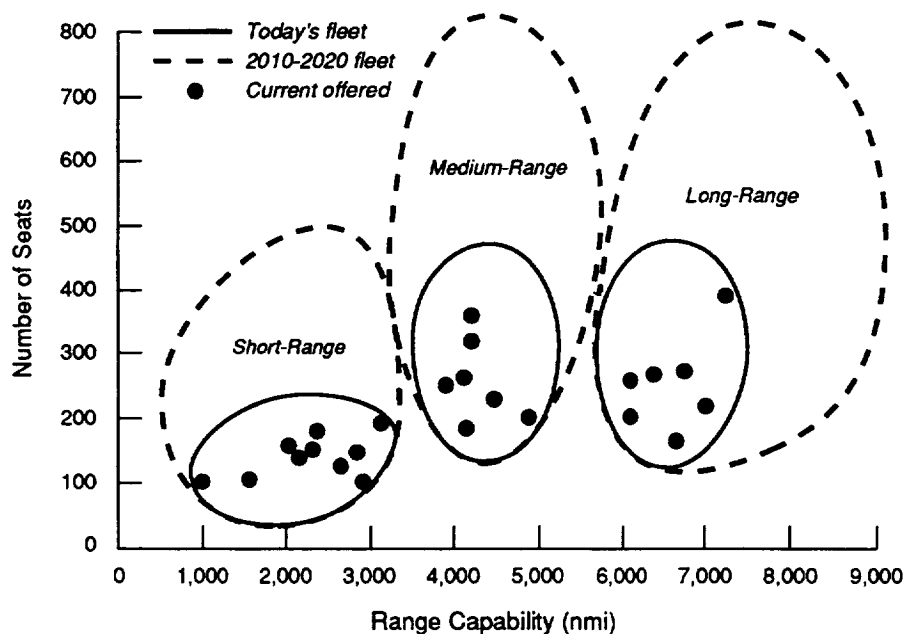


FIGURE 2-8 Number of seats versus range capability.

of current short-, medium-, and long-range aircraft identified by symbols that show specific aircraft. The data for current aircraft are extended by the dashed lines to show the probable course of the increase in size and passenger capacity of these categories.

The growth in size of transport passenger aircraft, particularly since the advent of wide-bodied designs, has increased the economic potential of large, dedicated all-cargo aircraft. A number of studies have been performed by NASA, Lockheed, General Dynamics, and Boeing of designs for aircraft with gross weights of 1 to 3 million pounds. Though infrastructure barriers exist, no technical barriers were identified in any of the studies. The reasons for the lack of success in this area are economic factors unrelated to the airplane itself. Nonetheless, a comprehensive aeronautics plan for the future should continue to examine the need for large passenger and cargo aircraft to determine whether aircraft technology might become the critical barrier to success.



## **BARRIER ISSUES**

Increased competition within the aircraft manufacturing sector and the pressures exerted on airlines by deregulation and uncertain fuel costs, have caused the development of new generations of aircraft to be increasingly driven by profitability. New aircraft designs incorporate only those features that can convincingly be shown to increase safety, reduce cost, or increase productivity, and any effort to develop advanced technology is viewed from that perspective. Furthermore, future aeronautical development programs not only must provide clear economic improvements, they must do so with minimum environmental effects and with an increase in safety such that the rate of accidents continues to decrease.

To meet the challenges of the next several decades, the Committee believes that each of the five areas of need described in Chapter 1 must continue to be addressed. However, for the particular needs of advanced subsonic transports, the Committee has concluded that three of those areas provide the primary new barriers to growth: overall cost, system capacity, and environmental compatibility. This is not to imply that performance and safety should be ignored. For example, it has been pointed out that a long-range, advanced subsonic aircraft with a cruise Mach number of 0.9 may provide a significant competitive edge. Rather, the Committee believes that sufficient safety and performance advancements can be realized by proceeding along the same general paths in structures, propulsion, aerodynamics, safety research, human factors, and cognitive engineering as have traditionally been followed. In contrast, to produce corresponding gains in cost, capacity, and environmental compatibility it will be necessary to rethink a number of the basic assumptions on which the current airspace system is based. Where appropriate, in the following sections the Committee has identified specific goals that it deems to be both necessary and reasonable for overcoming these barriers.

### **Overall Cost**

It is clear that the acquisition and maintenance costs of transport aircraft must be reduced to compete with increasingly sophisticated foreign competition. A reasonable goal is to reduce these costs by 25 percent over the next two decades, relative to currently produced airplanes. Likewise, operating costs must be reduced. A reasonable goal to bring that about is a reduction in fuel burn per seat of about 40 percent, compared to current airplanes. A 25 percent reduction can be expected from improved engine performance (Figure 2-9) and 15 percent from aerodynamic and weight improvements.

Figure 2-10 shows the achieved and anticipated improvements in aerodynamic efficiency from 1960 to 2020. Over the 20 years from 1975 to 1995, aerodynamic efficiency will have increased by less than 10 percent. This trend indicates that through normal evolutionary advances, lift-to-drag (L/D) ratios will reach only 22–25 by 2020. More aggressive application of aerodynamics technology could push this ratio to 28–30 and provide a significant competitive advantage for U.S. aircraft.

The historical trends in aircraft weight improvements are not as clear. Improvements have been offset in the past by improved operational performance, which includes greater range,

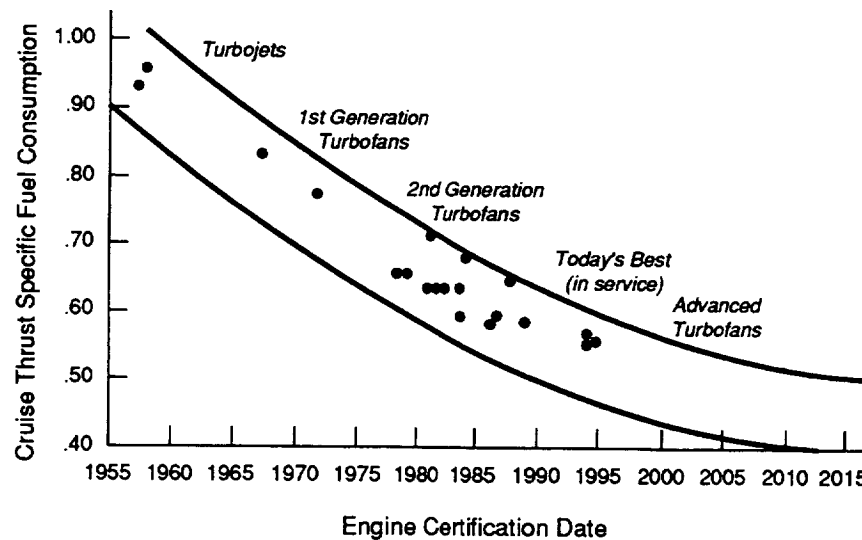


FIGURE 2-9 Installed turbine engine efficiency (TSFC = thrust-specific fuel consumption).

better altitude capability, better low-speed performance, lower noise, wide-body comfort, better cargo handling, improved systems response/redundancy, and longer structural life. For the future, composite structures appear to provide the most attractive improvements (Figure 2-11), but a great deal of research is needed into processes for evaluation, maintenance, and repair of composite structures. Additional features, however, are expected to be added to the aircraft, which will offset some of the gains. At current prices and for an airplane the size of a 747-400, these gains translate into a 26 percent reduction in DOC, as illustrated in Figure 2-12. For a broader range of sizes these goals are shown in Figure 2-13.

### System Capacity

The complexity and congestion of the current airspace system and the corresponding congestion at the world's airports suggest that realizing the expected growth in the advanced subsonic transport market will require a significant change in the approach to accommodating people and aircraft. It is clearly impossible to continue building larger and larger aircraft and to expect current airports to accommodate them. Nor is it reasonable to think that more and more aircraft, with the current level of air traffic control, will be able to fit into the already crowded airspace without seriously affecting safety and convenience. Without advancements in on-board control and warning systems, systems that make better use of global positioning satellites for flight path design, and systems that make it possible to accommodate more passengers and planes both in the air and on the ground, the future of air travel will be one of longer delays and more accidents. Chapters 10 and 11 of this report describe technologies that

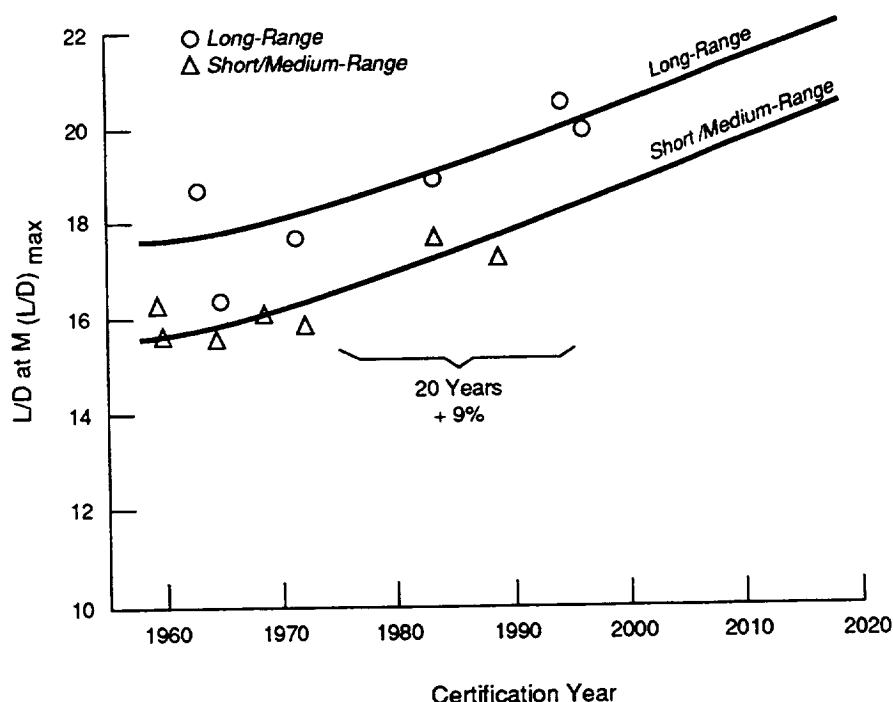


FIGURE 2-10 Aerodynamic efficiency.

are deemed by the Committee to be of primary importance in providing these required capabilities.

### Environmental Compatibility

The environmental compatibility of large subsonic transports is a major barrier to the growth of the worldwide market and, thus, to the growth of U.S. companies that build this type of aircraft. Although it is impossible to predict the requirements that will be placed on future systems regarding engine emissions, it is clear that they will be significantly more restrictive than current regulations. Similarly, a reduction in noise that is sufficient to satisfy continually more stringent regulations will be essential to remaining competitive over the next several decades.

There has also been much discussion regarding the use of exotic fuels such as liquid hydrogen or liquid methane to reduce fuel costs or noxious emissions. The Committee believes that such fuels will probably not be required in the period 2010–2020. Rather, synthetic Jet A-1 fuel can likely be produced from oil shale, natural gas, and coal at significantly lower total costs than these exotic fuels when all factors are considered.<sup>6</sup>

<sup>6</sup> National Research Council. 1990. *Fuels to Drive our Future*. Washington, D.C.: National Academy Press.

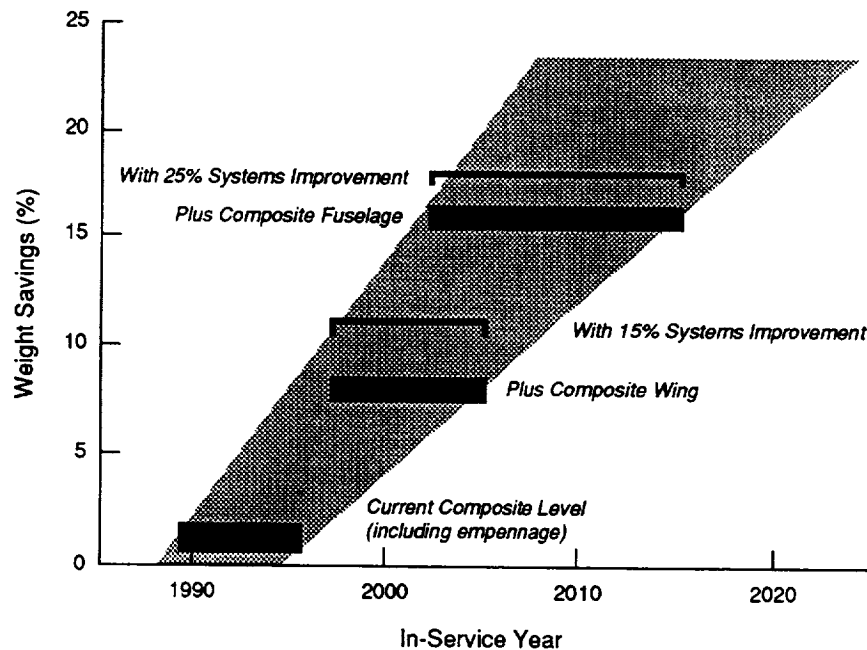


FIGURE 2-11 Potential airframe weight savings.

## NASA'S CONTRIBUTIONS TO ADVANCED SUBSONIC TRANSPORTS

The contributions that NASA can make to the development of technology for advanced subsonic aircraft are grouped below into the five categories of need that were defined in Chapter 1: cost/convenience, system capacity, safety, environment, and aircraft performance. As might be expected, much of this discussion overlaps with the corresponding discussion of NASA's contributions to the advancement of HSCT and short-haul aircraft (Chapters 3 and 4, respectively). Although the factors that make an aircraft competitive vary somewhat by category, the technologies that make for better performance, simpler and safer coordination with the air traffic management system (ATM), or reduced impact on the environment tend to be applicable to a variety of aircraft. Thus, the issues discussed in this section may well apply to other categories of aircraft as well. Table 2-2 shows current (1992) funding for advanced subsonic transports by discipline. As discussed in Chapter 1, the Committee was not constituted to recommend specific funding levels for the technologies discussed in this report. Although the percentages shown in Table 2-2 seem appropriate given the wide range of technologies that are likely to contribute to the long-term success of subsonic aircraft, the technologies recommended here and in later chapters will require an increase in funding and possibly a change to the relative funding between disciplines. The precise increase in funding and the corresponding percentages devoted to each discipline should be determined by the NASA Office of Aeronautics and Space Technology as part of a continuing reevaluation of its program. This reevaluation

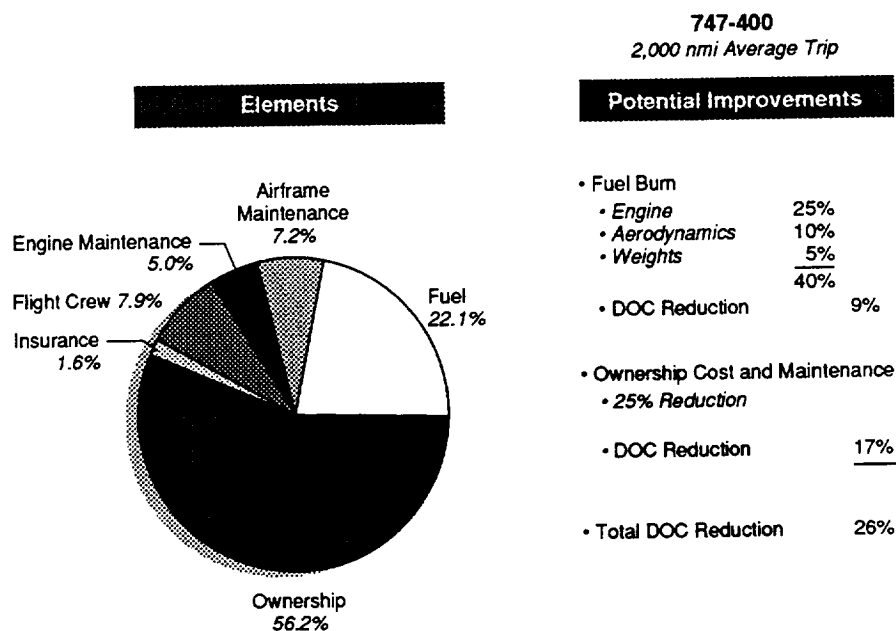


FIGURE 2-12 Direct operating cost breakdown for the 747-400 (1990 U.S. dollars).

should take into account the needs of industry and the current plans of other government agencies, particularly the FAA.

It should be noted that performance improvements required for future advanced subsonic transport aircraft are heavily dependent on the realization of significant advances in avionics and controls. Chapter 10 discusses these issues in detail. Some of the more important ones lie in the following categories:

- operational all-weather takeoff and landing systems,
- advanced ground control systems,
- integrated ground/air-based collision avoidance systems,
- airborne and ground-based, real-time, weather threat displays and alerting systems,
- cockpit display technology,
- relaxed static stability,
- integrated controls, and
- active flight controls.

Discussion of these points later in the report should not be construed to imply that there are no relevant NASA efforts. In many cases, NASA has productive ongoing programs. No attempt is made here to discuss or evaluate those efforts; rather, the Committee believes that they are not large enough to meet the needs.

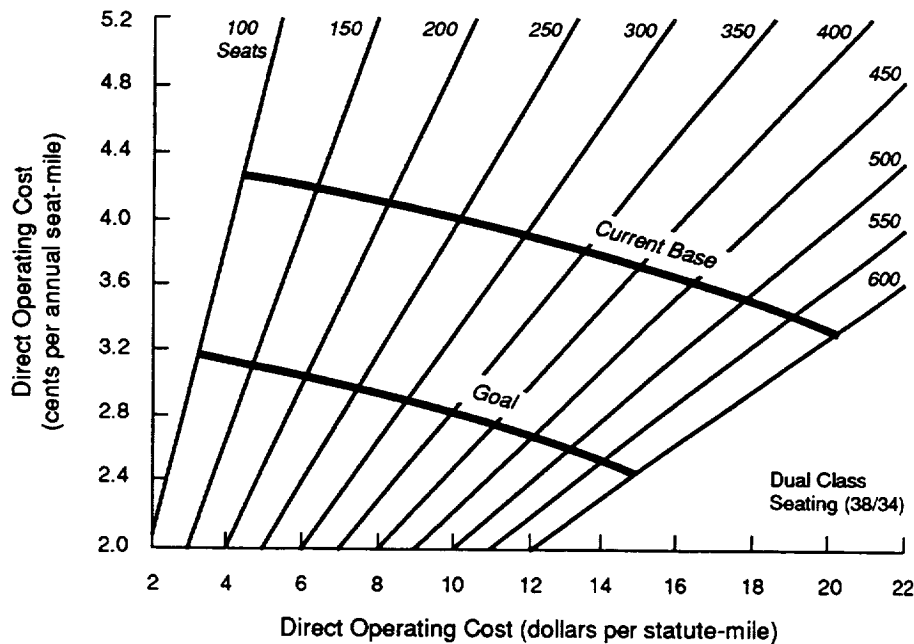


FIGURE 2-13 Direct operating cost goals (range = 1,000 nautical miles, 1990 U.S. dollars).

### Cost/Convenience

The Committee has identified a number of areas in which NASA can contribute to making advanced subsonic transport aircraft more cost-competitive while maintaining the overall convenience of both air and ground systems. In many of the following cases no specific technology will meet the stated goals. Rather, a combination of disciplines, some of which only NASA can provide, must be brought to bear on the problem. Thus, although the search for specific solutions to many of the following issues must remain the province of the private sector, NASA can expect to be a valued partner in the problem-solving process.

Aging aircraft require extensive, expensive, and numerous periodic airframe structural inspections to ensure structural integrity. The inspections themselves, the repair of damaged components, and the need to withdraw the aircraft from service for these activities all have unfavorable effects on cost. The economic airframe structural life of jet-powered subsonic transport aircraft as a design requirement has increased from an initial 10 or 12 years for the early designs in the 1950s, through 15 years, and now 25 years for new designs. Pressure for this continuing increase comes from the disproportionate increase in labor costs associated with a given level of inspection and repair. Composite structures promise major improvements in aircraft weight but will not be widely used in commercial aircraft until their cost is reduced and confidence in their structural life has increased greatly. That is, composite structures must not require major modifications to maintain structural integrity during their projected economic life. Clearly, NASA should use its growing expertise with new composite structures to help guide

TABLE 2-2 Advanced Subsonic Transport Funding by Discipline

Discipline	Current NASA Program (millions of 1992 dollars, percent of total) <sup>a,b</sup>	
Systems and operations <sup>c</sup>	2.3	2.4%
Aerodynamics	12.9	13.8%
Propulsion	16.8	18.0%
Structures and materials	28.1	30.1%
Controls, guidance, and human factors <sup>d</sup>	29.4	31.4%
Other (aging aircraft)	4.0	4.3%
<b>Total</b>	<b>93.5</b>	<b>100.0%</b>

Source: NASA Office of Aeronautics and Space Technology.

<sup>a</sup> 1992 funding in real-year dollars, excluding fundamental research not tied to a specific application.

<sup>b</sup> Percentages may not add to 100% due to roundoff error.

<sup>c</sup> Includes both flight systems research and systems analysis studies.

<sup>d</sup> Includes the avionics and controls and cognitive engineering categories discussed in this report.

the aircraft manufacturing industry in determining how the greater use of composites can reduce the weight of aircraft without adversely affecting economic lifetime. Also, current European aircraft are deemed superior to U.S.-built designs in their corrosion resistance. NASA should work toward a significant improvement in the understanding of corrosion resistance in an effort to help lengthen the period between mandatory inspections.

A major element of airline operating costs is spare parts with the associated maintenance and man-hour costs. NASA should intensify its efforts to improve the reliability and maintainability characteristics of aircraft components, particularly in reducing the complexity of components such as actuators, pumps and valves, and engines. Also, items such as fasteners, connectors, wiring, and reduced-sensitivity avionics should be considered.

Basic landing gear components such as wheels, tires, and brakes also contribute significantly to operating costs. In fact, they are the highest maintenance item on a per-flight basis. As aircraft weight increases, landing gear weight and complexity increase disproportionately. If aircraft weights continue to grow as forecast, efforts to simplify the design and reduce the cost of landing gear components will provide increasingly important cost savings. NASA should use its facilities and expertise to contribute to a significant decrease in both the weight and the complexity of landing gear components.

Modern developments in secondary power systems (i.e., electrical and pneumatic subsystems) may reduce or eliminate the need to use engine bleed air as a power source, thereby reducing fuel consumption. Research in "power by light" systems has shown promise, at least for low power levels, but much refinement is needed. In short, secondary power systems should be independent of the operation of the main propulsion engines, although backup systems that are driven by the main propulsion engines should certainly be available. The use of high-performance battery systems being developed for a variety of nonaircraft uses, as well as electrostatics technology, should be explored. **NASA should play a key role in developing advanced power technology, for applications in aeronautics, to the point at which industry can begin incorporating it on a large scale.** NASA's current research into advanced power systems for spacecraft may provide applications in this area.

Present-day aircraft suffer from cockpit suites designed and manufactured by a number of different companies, which produce mismatches in capability and less-than-optimal performance. Typically, displays and other components are selected by airline operators from various manufacturers, leaving the aircraft manufacturer the very difficult task of integrating the assortment of components. Given this difficulty, manufacturers have begun to explore fully integrated cockpit concepts. Unfortunately, this is an area in which both the Japanese and the Europeans offer significant competition. **NASA should help provide the technology needed to stave off this competition. Application of flat panel displays to replace cathode ray tubes, advanced computing and information-sharing technology, integration standards, and applications of advanced human factors can all contribute.** Furthermore, a coordinated systems engineering approach to cockpit development will be required to realize the full potential of this technology.

A major passenger complaint today is that comfort has deteriorated to very low levels. This can be an increasingly important competitive factor, and some passengers alter their travel routes to avoid certain airlines and take more circuitous routes that offer a higher degree of comfort. In addition to the obvious consequences of inadequate seat width and knee room, it has long been known that prolonged exposure to decreased pressure, low humidity, high noise, and high vibration greatly increases passenger fatigue. It is within current engineering design capabilities to reduce any, or all, of these factors. However, the trade-off between aircraft weight and measures to reduce passenger fatigue presents a difficult decision for the designer. As an example, for every increase in minimum cabin pressure an aircraft requires a corresponding addition of structural weight. The question is whether such an increase in minimum cabin pressure would have any measurable effect on passenger fatigue. Further, no design guidance is available to answer the question of whether the weight penalty is better spent in this way than in using it to reduce noise or vibration, for example. **NASA should use its expertise in cognitive engineering to guide the designers of advanced aircraft in achieving real gains in passenger comfort and corresponding gains in the competitiveness of U.S. products.**

Chapter 1 of this report contains a short discussion of the benefits of reducing the design cycle time for aircraft to get new generations of products to market ahead of the competition. Although the Committee did not consider this issue in detail, it is worth mentioning that a major



factor in remaining competitive in the advanced subsonic transport market is the ability of aircraft manufacturers and airline operators to adjust rapidly to different passenger desires, changing fuel costs, changing routes, and changing regulations. This parallels the situation in the automobile industry, in which the Japanese can bring a completely new design to market in three years, whereas the U.S. industry takes five. It would be of significant benefit to the U.S. air transport industry if one year could be eliminated from the development time of an aircraft. The difficulty in accomplishing this will be increased by the additional efforts that must be devoted to safety and environmentally-driven items during the design process. The increasingly complicated certification process, although not directly a technology issue, may, nonetheless, produce difficulty in incorporating new technology into aircraft. NASA's role in this effort is unclear, but it is likely to involve no more than being an advisor to industry.

### System Capacity

System capacity was identified in the previous section as one of the primary barriers to growth of the advanced subsonic aircraft market. The Committee has identified a number of areas in which NASA can contribute to increasing the capacity of air and ground systems.

To maximize terminal airspace use, aircraft separation currently required to account for wake vortex effects should be reduced. **NASA should investigate the potential reductions that can be realized in wake vortex effects through detection and avoidance, through understanding the effects of meteorology, and through reducing of the rotational energy in the vortices by means of aerodynamic design refinements.**

Better and more reliable electronic and mechanical systems, along with more straightforward maintenance procedures, will materially assist in achieving greater reliability in aircraft. Currently, airlines are capable of 98 percent mechanical reliability in dispatching their planes. With efforts to develop more reliable components and to incorporate a design-for-maintenance approach into the total systems design process, that figure could increase to 99 percent. Similarly, greater reliability can reduce the amount of time aircraft spend on the ground, thereby freeing up airport gates for the next arriving flight and moving more people through the system.

Since major increases in the size of current airports are not feasible, a reduction in the physical dimensions of aircraft while on the ground is one approach to packing more aircraft into a limited space. New aircraft in the 700- to 800-seat category are already in the design stage, and a 1,000-passenger aircraft is quite possible by the year 2020. Neither these aircraft nor a reduced sonic boom HSCT will meet current airport dimensional limitations.

As noted earlier, the use of suitable satellite and inertial systems, coupled with data links, should be pursued intensively in an effort to eliminate ground-based systems for position fixing. A ground-based system will still be required to provide a check and backup in the event of loss of the satellite system. An additional objective is elimination of the need for a separate collision avoidance system. The ability to provide an even safer level of operation is inherent in the improved satellite/inertial system. Positive four-dimensional control will be needed for the capacity requirements and should ensure no collisions.

Category IIb operations are currently possible at only a few runways equipped with the necessary ground aids.<sup>7</sup> The use of sophisticated on-board systems, as discussed earlier, will eliminate this dependence and should enable true Category IIc operations with zero runway visual range. Category IIc will be required for the higher-capacity system needed for the period 2010–2020 to ensure that air traffic continues flowing smoothly in adverse weather conditions. In addition, advanced ground control systems will be necessary to ensure that aircraft can safely navigate on the ground in bad weather.

The attainment of safer and higher-density takeoffs/landings and en route separation requires a reduction in the demands placed on voice radio communications between aircraft and ground. This can be accomplished through air-ground data links for many ATM system messages. A related issue involves the growing use of higher-power ground- or sea-based high-intensity radio field transmitters. The effect of these transmitters on sophisticated aircraft electronics subsystems, particularly those associated with navigation and aircraft control, must be determined.

**NASA, in conjunction with the Federal Aviation Administration, must continue to work toward incorporating advanced positioning, collision avoidance, and information transfer technologies into integrated on-board control systems for both in-flight and ground operations.**

### **Environment**

The future levels of allowable aircraft noise and emissions are unknown, but whatever they are, future aircraft must satisfy applicable laws, rules, and regulations—and those regulations must be sensible, not arbitrary and uneconomic. For aircraft noise in the 2005–2020 period, a preliminary goal of 10 dB below Stage 3 is a very demanding objective; the final goals must be balanced against economic effects and other risks. A preliminary goal for engine nitrogen oxide (NO<sub>x</sub>) emissions is a reduction of 20–30 percent. Noise and emissions levels must be controlled without increasing costs or degrading performance. **It is the Committee's belief that NASA can and should play a lead role in addressing the problems associated with noise and emissions from advanced subsonic aircraft.**

### **Safety**

Air travel has become remarkably safe because much of industry's and NASA's efforts have focused on safety. The accident rate per departure is the most often cited figure of merit because aircraft risk is largely associated with landing and takeoff operations. The accident rate has stabilized in recent years. However, although the rate is relatively low, an increasing

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<sup>7</sup> Runway visual range (RVR) is the horizontal distance runway at which the pilot can actually see the landing position. Category IIb operations imply an RVR of approximately 300 feet. Category IIc operations imply zero RVR, or essentially zero visibility landing.

number of operations will increase the absolute number of accidents accordingly, which would be unacceptable. The industry believes that the rate of accidents per departure can be lowered sufficiently to hold the number of accidents per year constant through the next 10 years while still increasing the size of the fleet. Once this goal is achieved, other innovations not currently available will be needed to continue to lower the rate. Because 72 percent of all hull loss accidents are primarily crew related, emphasis on human factors is needed, as discussed in detail in Chapter 11. Since NASA has considerable experience in this area, the agency should provide a great deal of the effort toward pushing the state of the art in aircraft safety.

Considerable progress has been made in the area of wind shear detection, but false alarms and false indications are still concerns. A fully reliable wind shear prediction detection and avoidance system is mandatory for the 2010–2020 time period. As noted in the discussion of system capacity, development of sophisticated on-board inertial and satellite capability, permitting the elimination of ground-based microwave landing systems and instrument landing systems, will also eliminate the need for primary ground-based systems for position fixing (except as a backup in case of loss of the satellite system). **NASA should play a major role in the development of a broad range of ATM systems.**

Development of advanced flight simulators can have a pronounced impact on training and skill maintenance for commercial pilots. Although flight simulators have reached impressive levels of performance and simulation, their development cycle time is usually such that operators do not have access to them when they need them. It is desirable to have flight simulator development proceed along a schedule that matches the aircraft development and delivery schedule. This will also offer future operators the opportunity to uncover operational problems prior to delivery. NASA has considerable expertise in the development and operation of simulators for both aircraft and space systems. **It should work with industry to determine areas in which advanced technology can be applied to commercial aircraft simulators.** Potential applications include reduced cost, improved reliability, and overall fidelity.

### **Aircraft Performance**

NASA's role in pushing the state of the art in performance for advanced subsonic transports is clear: aircraft that have greater fuel economy, better lift-to-drag ratios, and lower structural weight are required to keep U.S. manufacturers competitive because they are the primary drivers of cost. NASA is, of course, a major contributor in advancing the technologies that produce those performance improvements through aerodynamics, structures and materials, propulsion, advanced avionics, and information sciences and human factors. Details of how these performance issues should be addressed in the current and future NASA aeronautics program are deferred to later chapters of the report that deal specifically with these disciplines.

**RECOMMENDED READING**

Boeing Aircraft Company. 1972. Study of the Application of Advanced Technologies to Long-Range Transport Aircraft. Volume I: Advanced Transport Technology Final Results (NASA CR-112092). Prepared for National Aeronautics and Space Administration under Contract No. NAS 1-10703.

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General Dynamics, Convair Aerospace Division. 1972. Study of the Application of Advanced Technologies to Long-Range Transport Aircraft. Volume II: Technical Applications (NASA CR-112092). Prepared for National Aeronautics and Space Administration under Contract No. NAS 1-10702.

Lange, R.H., R.F. Sturgeon, W.E. Adams, E.S. Bradley, J.F. Cahill, R.R. Eudaily, J.P. Hancock, and J.W. Moore. 1972. Study of the Application of Advanced Technologies to Long-Range Transport Aircraft. Volume I: Analysis and Design (NASA CR-112088). Prepared for National Aeronautics and Space Administration by Lockheed-Georgia Co., Lockheed Aircraft Corp., under Contract No. NAS 1-10701.

National Research Council. 1988. Look Ahead—Year 2020. Transportation Research Board. Washington, D.C.: National Academy Press.<sup>8</sup>

National Research Council. 1990. Fuels to Drive Our Future. Energy Engineering Board. Washington, D.C.: National Academy Press.<sup>8</sup>

Toll, Thomas. 1980. Parametric Study of Variation in Cargo-Airplane Performance Related to Progression from Current to Spanloader Designs. NASA Technical Paper 1625. Washington, D.C.: National Aeronautics and Space Administration.

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<sup>8</sup> These reports conclude that the supply of petroleum is adequate through the year 2020 and that if the price rises approximately \$70 per barrel, petroleum can be extracted from coal, tar sands, and shale at prices about this level. Boeing studies (and others) show that even at this price level, the equivalent of Jet A-1 will still be the preferred fuel.

## HIGH-SPEED CIVIL TRANSPORT AIRCRAFT

### INTRODUCTION

The United States had a government-funded supersonic transport (SST) program during the 1960s. That program was canceled in 1971 because of increasing concerns over economic viability, environmental acceptability, and the inadequate state of the needed technologies. Technology studies for a future SST continued in the National Aeronautics and Space Administration (NASA) at a low level of effort during the late 1970s and early 1980s.

The White House Office of Science and Technology Policy in 1985 and 1987 identified national aeronautical research and development goals and laid out an action plan for achievement of those goals.<sup>1,2</sup> One of the goals was technology development to support a long-range supersonic transport, which was referred to as "a great market-driven opportunity." The reports further recommended that industry and NASA determine the most attractive technical concepts and the necessary technological developments for future long-range, high-speed civil transports (HSCT).

This chapter discusses the Committee's findings and recommendations regarding the future of HSCT technology. The potential market for this class of aircraft is considered, and NASA's contributions to developing the needed technology are outlined. The boxed material summarizes the primary recommendations that appear throughout the chapter, with specific recommendations given in order of priority, and the benefits of research and technology development efforts for HSCT.

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<sup>1</sup> Executive Office of the President. 1985. National Aeronautical R&D Goals: Technology for America's Future. Report of the Aeronautical Policy Review Committee, Office of Science and Technology Policy. Washington, D.C.

<sup>2</sup> Executive Office of the President. 1987. National Aeronautical R&D Goals: Technology for America's Future. Report of the Aeronautical Policy Review Committee, Office of Science and Technology Policy. Washington, D.C.

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### Recommendations

#### General

NASA should be the primary contributor to technologies that identify and reduce the environmental impact of HSCT, including ozone depletion, airport noise and emissions, and sonic boom.

#### Specific

1. NASA should enhance its atmospheric research program to determine whether acceptable levels of ozone-depleting emissions from HSCT exist. If so, NASA should perform the necessary propulsion research and validation to meet those levels.
  2. NASA should work toward advances in HSCT propulsion technology that reduce noxious emissions and engine noise.
  3. The HSCT program should be tailored to ensure that propulsion, aerodynamics, structures and materials, and overall vehicle management and control technologies are adequately represented.
  4. Although industry is not currently planning HSCT supersonic flights over populated areas, NASA should continue an aggressive program to define acceptable sonic boom levels and should continue its program to investigate approaches to meeting those levels.
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## CURRENT INDUSTRY STATUS

In response to the Office of Science and Technology Policy reports, NASA initiated the High-Speed Civil Transport Study to investigate the HSCT technical feasibility, economic viability, and environmental compatibility, and to identify potentially high-payoff technology development for HSCTs. Original vehicle characteristics were not specified—industry contractors were encouraged to examine flight between Mach numbers of 2 and 25, with the associated vehicle requirements and characteristics. Those early studies determined that a market will exist for an HSCT.<sup>3,4</sup>

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<sup>3</sup> McDonnell Douglas Aircraft Company. 1989. Summary of High-Speed Civil Transport Study (NASA CR-4236). Prepared for National Aeronautics and Space Administration.

<sup>4</sup> Boeing Commercial Airplanes. 1989. High-Speed Civil Transport Study Summary (NASA CR-4234). Prepared for National Aeronautics and Space Administration.

**Benefits of High-Speed Civil Transport Research and Technology Development****Cost/Convenience**

## Competitive operating costs

Fuel consumption as low as possible

Maintenance and reliability competitive with advanced subsonic aircraft

Predictable airframe and component life

Adequate comfort levels for crew and passengers

Technology validation (to reduce development costs)

**Environment Compatibility**

Acceptable noise (airport noise and sonic boom)

Acceptable emissions

**Aircraft Performance**

Improved fuel economy (over first-generation supersonic transport)

Improved speed and range

Because of the distances corresponding to the identified markets, practical limits on vehicle operations that limit aircraft productivity, and the increase in required technology development, risk, and cost with increasing Mach number, it became apparent that only speeds at or below Mach 3.2 were feasible. More detailed analysis has indicated that for the near-term, economic competitiveness is enhanced at even lower cruise Mach numbers.<sup>5</sup> Economic viability requires that the cost and risk of developing advanced technology be balanced with the expected economic return when compared to the competing advanced subsonic systems of that time frame. The HSCT studies identified barriers to the potential operation of a supersonic transport. These barriers included adverse environmental impact, constraints on operations due to the environment, and insufficient technology to provide vehicle performance adequate to ensure economic viability. NASA instituted the High-Speed Research Program,<sup>6</sup> which involves NASA and industry together doing the research required to quantify and remove these barriers, and to develop a technology base to ensure that U.S. industry is in a strong competitive position for the design and development of an HSCT.

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<sup>5</sup> Samuel M. Dollyhigh. 1989. Technology Issues for High-Speed Civil Transports (SAE Paper 892201). Society of Aerospace Engineers.

<sup>6</sup> NASA Office of Aeronautics, Exploration and Technology. 1990. High-Speed Research Program. Program Plan. Washington, D.C.

The Concorde, a first-generation SST built by a British and French consortium, is generally considered to be a technical success but an economical failure. A small number of these planes are in service, catering to a small segment of the first-class market, where very high fares and government subsidies support the substantial operating costs. The Soviets built an airplane very much like the Concorde (the Tupolev-144), which had very limited operation.

Currently, many research and development programs relative to a second-generation supersonic transport are underway in foreign countries. The French are working on the second-generation Concorde.<sup>7</sup> The Japanese, although currently limited in aeronautical technology capability, have the interest and capital to pursue an advanced supersonic transport. Representatives from the former Soviet Union are pursuing a cooperative venture with Gulfstream Aerospace in this country for the development of a supersonic business jet, as well as various cooperative ventures with the Europeans.

Even if environmental problems are solved, bringing an HSCT from initial research and development to operation will still require a substantial investment. The demand for an HSCT fleet, although substantial, may support only one development program.

## MARKET FORECAST

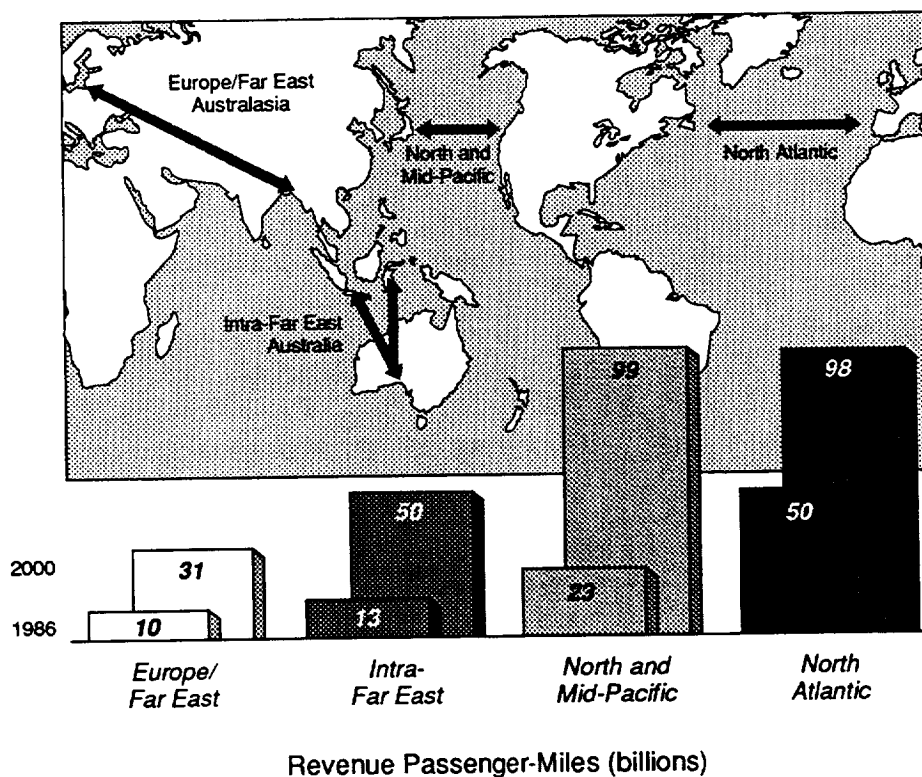
National and international air transportation systems are growing. Increases of about a trillion revenue passenger-miles are projected for each decade between now and the year 2020, resulting in two trillion revenue passenger-miles in 2000, three trillion in 2010, and four trillion in 2020. Much of this growth is projected to be in international markets (Figure 3-1). The North Atlantic market is expected to double by 2005, but more importantly the Pacific market (with its longer ranges) is forecast to quadruple during this time to about the same size as the North Atlantic market. The Europe-Asia market is also projected to experience significant growth. Based on these market projections, if a reasonable fare premium (10–20 percent) is assumed, an HSCT is optimistically thought to be able to attract about 300,000 passengers per day away from advanced subsonic transports by the year 2000, and about 600,000 passengers per day by 2015.<sup>8</sup> This translates into a worldwide potential market for 600 to 1,500 HSCTs, depending on economic returns, aircraft specifications, operating constraints, and subsonic flight over land. Although these optimistic projections depend strongly on various economic factors, the number of aircraft is sufficient to be economically viable for an airplane manufacturer.

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<sup>7</sup> Ph. Poisson-Quinton. 1990. What Speed for the Next Generations of High Speed Transport Airplanes—Supersonic or Hypersonic? France: ONERA.

<sup>8</sup> Boeing Commercial Airplane Company. 1989. High Speed Civil Transport Study. NASA Contractor Report 4233.





Source: Sams, H. 1989. SSTs, HSTs, and SSTO and Lessons Learned. Aeronautical Design Symposium.

FIGURE 3-1 International passenger traffic.

## BARRIERS

To be successful, the HSCT must be economically viable, environmentally compatible, and technically feasible. Economic viability will be attained if the value of the HSCT to the airline is at least as great as the price charged by the manufacturer and the cost of ownership. Environmental acceptability includes no significant effect on the ozone layer, acceptable sonic boom levels, and community noise levels that meet future regulations.

### Economic Viability

Currently envisioned HSCT configurations, which take advantage of either current or very near-term technology and could be introduced in the 2005 time frame, cruise at speeds of Mach 1.6–Mach 2.5, have ranges between 5,000 and 6,500 nautical miles, carry 250 to 300 passengers, and operate in the existing infrastructure (airports, runways, and air traffic management system) to maximize productivity. Since the HSCT will probably be 50 to 100 feet longer than today's Boeing 747, innovative ground operation and passenger loading/unloading

techniques may be required. Additionally, the HSCT must permit rapid turnaround time to allow airlines to use the aircraft to its fullest potential.

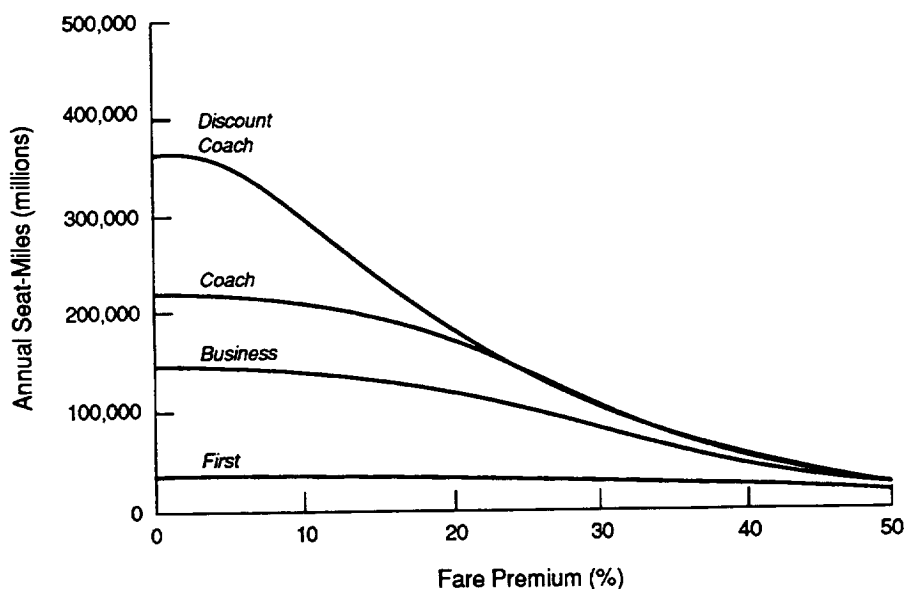
The value of an HSCT to the airline must be at least as great as the price charged by the manufacturer. Value to the airline is dependent on the cost of owning and operating an HSCT fleet, on being able to attract a sufficient number of revenue passengers, and on attaining high productivity. The costs of ownership and operation are dependent on the aircraft technology level, the number of aircraft produced, and outside economic factors (e.g., fuel cost and interest rates). Productivity increases as the airplane's speed, capacity (number of passengers), and rate of utilization (flights per day) increase. The number of passengers depends on several factors, including the market, the perceived benefit of this type of flight, and the ticket cost. The rate of utilization of an HSCT may be limited by scheduling and turnaround times.

As noted in the introductory section of this chapter, much of the growth in the air travel market is projected for the long-range international market. The flight times on these routes are long (13 to 14 hours) for subsonic aircraft; the HSCT could cut this time in half. This reduced flight time is attractive to passengers for both the actual time saving and the decreased fatigue. However, reduced flight time will not be sufficient to lure the traveler away from the advanced subsonic transport unless the fare is competitive. Figure 3-2 is an estimate of how much extra the passenger is willing to pay for faster service. The figure shows how many available seat-miles can be captured as a function of fare premium. For example, a fare premium of 10 percent would capture a total of approximately 300 billion seat-miles annually, whereas a fare premium in excess of 20 percent would result in only about 200 billion available seat-miles. To attract the discount coach passenger market, the fare premium must be no more than 5 to 10 percent (the discount coach market accounts for about 40 percent of the overall market).

Productivity for airline operators increases as a result of the HSCT speed advantage. For example, an HSCT traveling at twice the speed of a subsonic aircraft can carry a comparable load of passengers twice the distance in a given time (if the time to climb and descend, as well as time on the ground for servicing and refueling, is a small part of the total travel time) or can make twice as many trips over a given distance in a given time. For a successful HSCT, increased productivity would be due to a greater number of seat-miles deliverable each day compared to subsonic aircraft of the same capacity, provided the air traffic management (ATM) operations, airport operations, maintenance, and turnaround times can be held low enough so as not to offset the greater productivity enabled by higher-speed flight. Balanced against this are the direct costs per seat, fuel consumption per seat-mile, and maintenance costs per seat-mile, which are higher for an HSCT than for competing subsonic aircraft.

### **Environmental Viability**

Economic viability is a necessity for the HSCT; so is environmental compatibility. Atmospheric emissions and community noise constraints must be satisfied or there will not be an HSCT program. The issue of sonic boom can be dealt with by allowing supersonic flight only over water (the current rule), but there is a resulting economic penalty in having to fly at subsonic speed over land.



Source : National Aeronautics and Space Administration

FIGURE 3-2 Market capture.

The emissions from any aircraft engine include nitrogen oxides which, together with sunlight, generate ozone and other strong oxidants in the lower atmosphere. In the stratosphere, however, nitrogen oxides destroy naturally occurring ozone; unfortunately, stratospheric ozone destruction cannot be compensated by its production at lower altitudes. This is especially a problem with supersonic aircraft whose optimum cruise altitude coincides with the region of highest ozone concentration. One potential solution is to reduce the cruise Mach number (from Mach 3.2 to the Mach 1.6–2.4 range) and, hence, reduce the optimum cruise altitude, thereby reducing the effects on ozone. Continuing atmospheric studies are needed to understand and determine the emission levels, if any, that do not reduce ozone concentration. Technology development (primarily low-emission combustors for the engine) focused on reducing nitrogen oxides to that level is necessary to meet this challenge.

To maintain high levels of productivity, the HSCT must be able to operate out of the same airports as competing subsonic transports. This implies that the HSCT must produce community noise levels no higher than its subsonic competition. Those levels vary widely by locality but are well-defined in most developed countries, and at this time the HSCT cannot meet them. Furthermore, by the time an HSCT is flying, ground noise limits may be even more restrictive as individual communities become increasingly involved in setting their own noise levels.

The propulsion system is the primary source of noise during HSCT operation: however, the choice of flight path can have an impact on the overall noise level at and around airports. Innovative propulsion concepts are required to reduce engine noise, and good high-lift aerodynamic characteristics can provide flight paths that minimize noise outside the airport boundaries. Interpretation of the noise regulations for HSCTs that would allow higher noise levels inside airport boundaries could result in decreased noise in the community around the airport.

Sonic boom is probably the most controversial of the environmental issues. Yet it has a simple solution: never generate a sonic boom over land. However, significant costs are associated with scenarios that force supersonic aircraft to slow to subsonic speeds over land. If supersonic flights were allowed over land, the economic viability of the HSCT would be greatly enhanced because of the additional markets that could be served and would probably result in the construction of a greater number of aircraft. Additionally, designing an aircraft that shifts easily from supersonic to subsonic flight as it passes over land, while remaining competitive with advanced subsonic aircraft, is a significant engineering challenge.

The alternative, of course, would be to provide an aircraft that produces a sonic boom level acceptable to the community. This is difficult, especially because the level the community can accept is unknown and surely varies from place to place. Current rules in most countries categorically prohibit aircraft from generating sonic booms over land. During the SST development program, there was a belief that a low sonic boom level (perhaps 1 pound per square foot) would potentially be acceptable for overland supersonic flight. However, there still is no standard defined for an acceptable sonic boom level, and it is doubtful that 1 pound per square foot would be acceptable today. Technologies to reduce the sonic boom level and shape the sonic boom signature so as to minimize the annoyance are required, along with a definition of the acceptable level.

## **NASA'S CONTRIBUTIONS TO HIGH-SPEED CIVIL TRANSPORT**

Studies to date have shown that, if the cost is low enough, a substantial potential market exists for an HSCT. Foreign competitors are also working to capitalize on the market opportunity. The demand for an HSCT fleet, although substantial, may support only one development program. Potentially even worse for the United States than the loss of the HSCT market would be the associated reduction in the advanced subsonic transport market.

The success of HSCT depends on economic viability and its environmental compatibility. However, current technology is insufficient to produce a feasible HSCT. An aggressive technology development program is necessary to optimize the likelihood of achieving an environmentally compatible and economically viable HSCT to meet market demand. The United States must be in a good programmatic and technical position to be a key player (either alone or in an international consortium) in order to participate in the HSCT program.

Development of an HSCT represents a great deal more new development than the generally incremental improvements needed for short-haul and advanced subsonic aircraft. The primary issue facing the HSCT is its environmental compatibility—engine emissions, sonic

boom, and engine noise. In light of this, the Committee did not go into detail in defining the cost, safety, and ATM system implications of an HSCT, so the following discussion concentrates on technologies that NASA can help develop to push the state of the art in performance and to meet environmental requirements. Still, it is the belief of the Committee that, since the ultimate goal of the HSCT is to capture a significant portion of the market currently held by subsonic transports and to open up new markets, the technologies that enhance safety and convenience, reduce cost, and allow the aircraft to mesh with the air traffic system cannot be ignored. So, the fact that these needs are not specifically called out in this section should not be construed to mean that they are unimportant—they were simply not dealt with at this early stage of HSCT development. Table 3-1 shows the current (1992) funding for HSCT by discipline. As shown in Table 3-1, the current emphasis in the NASA program is on the environmental compatibility of HSCT, and to a lesser extent on propulsion and materials technologies. Given the discussion in this chapter outlining the importance of solving the emissions and noise problems associated with supersonic flight, this emphasis is appropriate.

TABLE 3-1 High-Speed Civil Transport Funding by Discipline

Discipline	Current NASA Program (millions of 1992 dollars, percent of total) <sup>a,b</sup>	
Environmental	59.9	64.5%
Systems and operations <sup>c</sup>	0.6	0.6%
Aerodynamics	2.1	2.1%
Propulsion <sup>d</sup>	19.4	19.4%
Structures and materials	10.1	10.9%
Controls, guidance, and human factors <sup>e</sup>	0.7	0.7%
<b>Total</b>	<b>92.8</b>	<b>100.0%</b>

Source: NASA Office of Aeronautics and Space Technology.

<sup>a</sup> 1992 funding in real-year dollars, excluding fundamental research not tied to a specific application.

<sup>b</sup> Percentages may not add to 100% due to roundoff error.

<sup>c</sup> Includes both flight systems research and systems analysis studies.

<sup>d</sup> Includes \$16.5 million for propulsion enabling materials.

<sup>e</sup> Includes the avionics and controls and cognitive engineering categories discussed in this report.

## Environment

As mentioned in the section on barriers to HSCT development, environmental impact may be the single most important discriminator in the feasibility of an HSCT. **NASA should continue to pursue technologies that reduce the environmental impact of HSCT and, thereby, eliminate a major barrier to its development. In particular, efforts to define acceptable sonic boom levels and research in mitigating ozone depletion may well provide the key factors that make an HSCT possible.**

NASA can, of course, make a major contribution to propulsion systems technologies that reduce both noise and emissions. This will require extensive development in the areas of high-temperature engine materials, cooling techniques, thrust and fuel management, and cycle performance improvements. In addition, inlet, engine, and nozzle integration depends on both analytical and experimental development of propulsion performance and control systems optimization.

In aerodynamics, development of a wing with good takeoff lift performance will help reduce community noise by allowing a steeper climb-out and concentrating the noise on airport property. Also, reduction of sonic boom levels without affecting overall performance is a matter that NASA is well suited to address.

## Aircraft Performance

Meeting the performance objectives of HSCT will require advances in four general areas: *propulsion, aerodynamics, materials and structures, and overall vehicle management systems.* The latter area would include the areas that are described in later sections of this report on advanced avionics and control systems, and cognitive engineering. **NASA should continue to tailor its HSCT program to ensure that these four areas are adequately represented.**

Advances in the propulsion system will require an improved mixed flow turbofan or variable-cycle engine using advanced materials that can provide greatly reduced emissions and propulsion system weight, and greater fuel efficiency over the entire range of flight conditions. However, the annual fuel consumption of an HSCT is still likely to be twice that of an advanced subsonic transport aircraft.<sup>9</sup>

Technology to improve aerodynamic performance (lift-to-drag ratio) is a constant goal in the development of all aircraft. For supersonic cruise vehicles, high lift-to-drag ratios are critical. Laminar flow control is an especially promising technology because it has the potential to minimize overall drag by directly reducing the friction drag component, which is a third or more of the total aircraft drag and indirectly reducing shock wave drag by lowering aircraft

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<sup>9</sup> For example, according to projections by the McDonnell Douglas Aircraft Company in 1989 (Study of High-Speed Civil Transports, NASA Contractor Report 4235) a Mach 3 HSCT would require approximately 0.2 pound of fuel per available seat-mile per nautical mile of range (lb/ASM-nmi). An advanced subsonic transport aircraft would require only about 0.05 lb/ASM-nmi.

weight and volume, because less fuel and smaller engines are required to overcome drag forces.<sup>10</sup>

Improved low-speed, high-lift aerodynamic performance for highly swept wings typical of a configuration designed for supersonic flight can positively impact noise. Although the propulsion system is the major contributor to noise during takeoff, as noted earlier the vehicle flight path and operations also affect noise impact on the community.

The key materials requirement for HSCT aircraft is for long-term stability of thermal and mechanical properties at sustained elevated temperatures and after years of routing operations over many thousands of thermal cycles. The challenge is to achieve this stability with the minimum material density while being able to fabricate and assemble the parts at reasonable cost.

Up to Mach 1.8, existing conventional metals and organic composites provide adequate performance. At Mach 2.4, titanium, reinforced aluminum, and high-temperature organic matrix composites provide adequate performance. The long-term stability and other durability and damage properties of the materials required for use at Mach 2.4 are not well understood, nor are the producibility characteristics well established.

From a structural standpoint, there are three primary issues. The first is to employ structural concepts that are economically producible with the chosen material systems. The second is to employ structural concepts that minimize the effects of thermal gradients in the structure. This issue becomes more critical as speeds increase beyond Mach 1.8. The third issue, which applies to HSCT aircraft that cruise above 40,000 feet, is to provide pressurized fuselage concepts that allow survivable cabin decompression scenarios.

Aircraft systems development is needed to provide the capabilities to operate the HSCT near optimum efficiency and to maintain safe operation. The technology for the HSCT includes flight and propulsion control systems, displays and navigational systems, and flight management of the aircraft.

To obtain good performance characteristics, an integrated flight/propulsion control system that addresses propulsion system control, propulsion effects on stability, control during low-speed flight, and acceptable flying qualities at all speeds must be developed. Advancements in integrated flight-critical control systems, fiber optics, synthetic vision, and integrated flight deck displays and management systems offer significant opportunities for implementing a vehicle management system that provides improved performance and safety for an HSCT.

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<sup>10</sup> NASA Office of Aeronautics, Exploration and Technology. 1989. High-Speed Research Program, Briefing Book. Washington, D.C.





## SHORT-HAUL AIRCRAFT

### INTRODUCTION

This chapter provides an assessment of the technology needs of short-haul aviation in the United States. It focuses on government research and technology development actions required over the next 10 to 20 years, with emphasis on the role of the National Aeronautics and Space Administration (NASA). The Committee believes that the recommended actions will provide U.S. manufacturers and operators with the technology necessary to take advantage of major opportunities projected for 2000 to 2020, and will help bring to the American public the benefits of a greatly improved short-haul air traffic management (ATM) system.

The chapter is presented in four sections: current industry status and environment, future needs and opportunities, barrier issues, and recommended NASA actions. In each section, items common to more than one category of short-haul aircraft are discussed first, followed by items specifically applicable to the individual aircraft categories. The boxed material summarizes the primary recommendations that appear throughout the chapter, with specific recommendations given in order of priority, and the benefits that can be expected from research and development efforts devoted to short-haul aircraft.

### CURRENT INDUSTRY STATUS<sup>1,2,3,4</sup>

The category of short-haul aircraft includes commuter aircraft, rotorcraft, and general aviation (GA) airplanes. Also, although not strictly short-haul aircraft, business and private jets are included in this category to distinguish them from large transport aircraft. There are roughly

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<sup>1</sup> Aerospace Industries Association of America. 1991. Aerospace Facts and Figures 91-92. Washington D.C.

<sup>2</sup> Regional Airlines Association. 1991. 1991 Annual Report of the Regional Airlines Association. Washington, D.C.

<sup>3</sup> Regional Airliner Census. 1991. Aerospace World Business & Technology. 5 (April).

<sup>4</sup> General Aviation Manufacturers Association. 1991. General Aviation Statistical Databook, 1990-1991 Edition. Washington, D.C.

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### Recommendations

#### General

NASA should enlarge its support of the key technologies for general aviation, commuter aircraft, and rotorcraft through extensive validation, and should both sponsor and participate in comprehensive system studies to define total aircraft systems, with investigations into their technical and economic characteristics.

#### Specific

1. NASA should undertake an aggressive safety research program focused on cognitive engineering and the features that are unique to the operation of commuter, rotorcraft, and general aviation aircraft.
  2. NASA's unique capabilities in simulation and training should be used to help enhance the initial training and skill maintenance programs of all aircraft pilots and mechanics.
  3. NASA's extensive capabilities in aerodynamics, structures, and acoustics should be applied toward major improvements in rotorcraft economics, speed, and efficiency.
  4. NASA and the FAA should undertake a study to establish the degree to which existing airport capacity could be increased by shifting some short-haul traffic to helicopters and tiltrotors, using vertiports integrated into available airport real estate.
  5. NASA should undertake an extensive research and technology development effort to improve rotorcraft passenger comfort.
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220,000 short-haul aircraft in the United States, making up 98 percent of the total civil aviation fleet.<sup>5</sup> Short-haul aircraft operations are projected to continue to grow with expansion of the national economy and growth of population and industry in communities remote from urban centers. The greatest growth is projected for the commuter sector, where passenger enplanements are expected to double during the 1990s.

European manufacturers in recent years have made major inroads in the markets for the various categories of short-haul aircraft. Foreign manufacturers, many of whom are subsidized by their governments, dominate the commuter market; currently no commuter aircraft for more than 19 passengers is being built in the United States today because manufacturers have found that they cannot compete in airframe manufacturing. However, a majority of commuter aircraft are powered by engines made in the United States or made elsewhere by U.S.-owned companies.

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<sup>5</sup> Aerospace Industries Association, op. cit.

**Benefits of Short-Haul Aircraft Research and Technology Development****Cost/Convenience**

- Development costs
  - Low cost components
  - Technology validation
- Reduced operating costs
  - Lower fuel consumption
  - Reduced maintenance
  - Longer airframe and component life
- Reduced liability costs
- Increased comfort levels for crew and passengers

**System Capacity**

- Reduced aircraft separation (takeoff and landing, on the ground, and in flight)
- Reduced complexity of ATM system
- Enhanced Category III operations

**Environment**

- Reduced noise

**Safety**

- Lower accident rate
  - Reduced human error
  - Reliable automated systems
  - Reduced and predictable aircraft fatigue

**Aircraft Performance**

- Greater fuel economy
- Greater speed and range

The following factors contribute to a continuing deterioration of the position of the U.S. manufacturers: the lack of capital in small U.S. aircraft companies, the establishment of a number of foreign consortia for development and production of commuter aircraft and rotorcraft, and the coordination and expansion of European technology development.

The April 1988 Euromart Study report<sup>6</sup> cited total research and technology development expenditures for commuter aircraft in Europe at \$450 million in 1986–1987; and recommended an immediate 25 percent increase, a 50–60 percent increase in 5 years, and a doubling in 10 years. These numbers include civil and military aircraft but exclude engine and equipment development.

### **The Commuter Market**

The commuters (regional airlines) provide air service to and from small- and medium-size communities. During the 1980s the developing "hub and spoke" patterns created a growth opportunity for commuters to feed the hubs. It created a growing interest by major air carriers in "code sharing" with regional carriers to provide integrated reservations, ticketing, and other services for traffic feed between major hub cities and smaller communities. Today, 94 percent of all commuter enplanements in the United States are made by code-sharing partners of major carriers.

Commuters are the fastest growing segment of the airline industry. During the past 10 years, there has been a threefold increase in the U.S. commuter airline business, from 14 million passengers annually to 42 million, and from 1.7 billion passenger-miles to 7.6 billion. The Federal Aviation Administration (FAA) forecasts<sup>7</sup> future growth at a somewhat lower rate, 7–8 percent per year, which is still a twofold increase over the next 10 years. Even this rate of growth is higher than that projected for the major carriers.

The average seating capacity of commuter aircraft today is 22.1 seats. They account for only 2 percent of scheduled carrier revenue passenger miles flown but for 8 percent of passengers, 35 percent of the aircraft in the fleet, and 40 percent of departures for scheduled air carriers. They are significant contributors to congestion at busy hubs and must compete for slots at capacity-controlled terminals.

As of February 1991, there were 2,534 commuter aircraft in service, of which 1,505 were in North America (see Table 4-1A). Only 565 of the 2,534 were manufactured in the United States. These aircraft carry 19 passengers or less, are made by Beech and Fairchild, and are based on original designs more than 20 years old. There are 1,363 announced orders for commuter aircraft, with only 87 of these orders placed with a U.S. company (see Table 4-1B).

Based on a forecast of the future commuter fleet by the Regional Airlines Association,<sup>8</sup> the U.S. market for commuter airplanes during the 1990s is estimated to be \$20 billion: 60 percent of the commuter market (\$12 billion) is projected for airplanes having a capacity of 40 passengers or more.

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<sup>6</sup> EUROMART Study Report. 1988. Loughton Essex, U.K.: Specialized Printing Services, Ltd.

<sup>7</sup> Federal Aviation Administration. 1991. Aviation Forecasts, Fiscal Years 1991–2002 (FAA Report FAA-APO-91-1). Washington, D.C.: U.S. Government Printing Office.

<sup>8</sup> Regional Airlines Association, op. cit.

TABLE 4-1(A) Short-Haul Aircraft Delivered, by Region (as of February 1, 1991)

Category	Europe	Middle East Africa	South America Caribbean	North America	Asia Pacific	Total	% Share
<b>10-19 passengers</b>							
BAe Jetstream 31	29	2	—	251	8	290	30
Beech 1900C	5	13	—	176	12	206	22
Dornier 228	47	32	13	39	53	184	19
Fairchild Metro III	30	2	5	235	3	275	29
Subtotal	111	49	18	701	76	955	
% share	12	5	2	73	8		
<b>20-40 passengers</b>							
DHC Dash 8-100	28	3	5	158	13	207	23
Embraer Brasilia <sup>a</sup>	42	1	10	155	2	210	23
Saab 340 A/B	85	—	3	117	14	219	24
Shorts 330/360	71	1	4	167	37	280	31
Subtotal	226	5	22	597	66	916	
% share	25	1	2	65	7		
<b>More than 40 passengers</b>							
ATR 42	57	13	10	92	15	187	28
ATR 72	13	—	—	2	5	20	3
BAe ATP	22	2	—	6	0	30	5
BAe 146-100	8	5	—	3	14	30	5
BAe 146 200	28	1	5	53	11	98	15
BAe 146-300	16	—	—	5	15	36	5
CASA/IPTN CN-235 <sup>b</sup>	20	13	6	—	14	53	8
DHC 8-300	12	—	4	19	2	37	6
Fokker 50	65	5	—	—	35	105	16
Fokker 100	26	2	2	27	10	67	10
Subtotal	267	41	27	207	121	663	
% share	40	6	4	31	18		
Total	604	95	67	1,505	263	2,534	
% share	24	4	3	59	10		

Source: Aerospace World Business and Technology

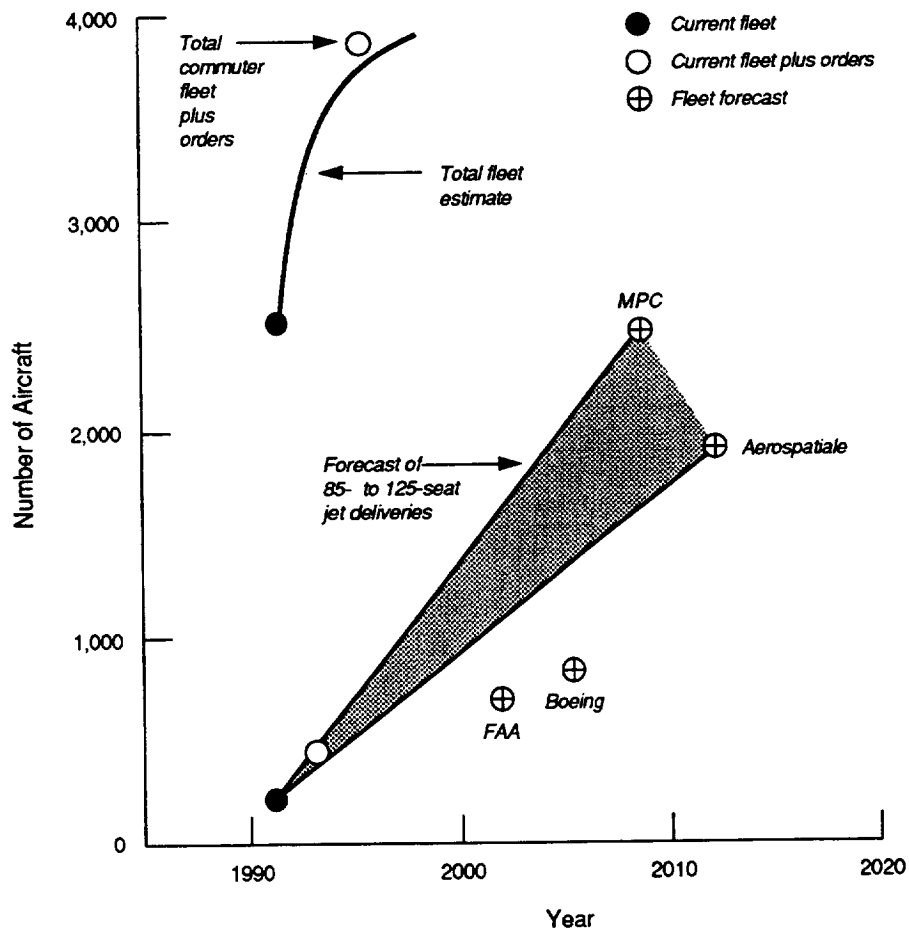
<sup>a</sup> Plus two undisclosed<sup>b</sup> Plus one undisclosed

TABLE 4-1(B) Short-Haul Aircraft on Order, by Region (as of February 1, 1991)

Category (passengers)	Europe	Middle East, Africa	South America, Caribbean	North America	Asia, Pacific	Total
<b>10-19</b>						
BAe Jetstream 31	2	—	—	27	3	32
Beech 1900C <sup>a</sup>	—	—	—	—	—	—
Beech 1900D <sup>a</sup>	—	—	—	—	—	—
CBA-123 Vector <sup>b</sup>	—	—	—	—	—	—
Dornier 228	—	—	—	—	5	5
Fairchild Metro III	—	1	27	59	—	87
Subtotal	2	1	27	86	8	124
<b>20-40</b>						
BAe Jetstream 41	—	—	—	10	—	10
DHC Dash 8-100	8	—	—	32	—	40
Dornier 328	3	1	—	33	4	41
Embraer Brasilia	6	1	1	98	—	106
Saab 340 A/B	16	—	—	92	7	115
Shorts 330/360	—	—	—	4	—	4
Subtotal	33	2	1	269	11	316
<b>More than 40</b>						
ATR 42	72	3	11	51	8	145
ATR 72	88	1	2	80	15	186
BAe ATP	—	1	—	8	—	9
BAe RJ70 <sup>c</sup>	—	—	—	—	—	0
BAe 146-200	16	—	—	—	1	17
BAe 146-300	4	—	—	—	9	13
Canadair RJ <sup>d</sup>	55	—	—	50	4	109
CASA/IPTN CN-235	29	53	—	—	38	120
DHC 8-300	39	—	5	21	6	71
Fokker 100	67	—	2	95	15	179
Fokker 50	23	—	—	—	2	25
Saab 2000	34	—	—	13	2	49
Subtotal	427	58	20	318	100	923
<b>Total</b>	<b>462</b>	<b>61</b>	<b>48</b>	<b>673</b>	<b>119</b>	<b>1,363</b>

Source: Aerospace World Business and Technology

<sup>a</sup> Beech Aircraft does not release order data.<sup>b</sup> Embraer has 99 options.<sup>c</sup> BAe had 10 options.<sup>d</sup> Includes orders and commitments.



Source: Aerospace World Business and Technology

FIGURE 4-1 Commuter fleet forecast.

The industry has been moving rapidly toward larger aircraft, with the hub bypass market being a significant growth opportunity. Worldwide, 923 of the 1,363 commuter aircraft on order are 40- to 107-passenger aircraft, and 318 of these are for the North American market (Table 4-1B). With the emerging fleet, the average capacity will grow from 22.1 to more than 40 seats. The aircraft on order include 328 jets; 219 of these are 100-passenger class, and 109 are 50-passenger aircraft.

A newly formed European consortium led by Deutsche Aerospace, along with Aerospatiale and Alenia, seeks to bring together a family of existing and new aircraft types to meet nearly all the requirements of regional airlines. This organization would parallel the Airbus Industries consortium which has complete medium- and long-haul product lines. They plan two basic new regional jetliners, one carrying 85-90 passengers and the other 120-125 passengers.

The forecast of jet deliveries to regional airlines (Figure 4-1) indicates that between 70 and 135 jet aircraft are expected to be delivered each year for the next 20 years by European manufacturers. The 219 100-seat aircraft on order illustrate the market trend.

Once technical suitability has been established, price and financing terms are the primary determinants of purchase, with operating costs secondary. Government-subsidized foreign manufacturers dominate the market, and competition among them is fierce. There are five manufacturers in the 10- to 19-passenger and six in the 20- to 40-passenger category. Seven manufacturers offer 12 models in the over-40 passenger category; however, there are currently only two competitors making 100-passenger jets, British Aerospace and Fokker; Canadair is developing a 50-passenger jet.

The market for smaller, less than 50-passenger aircraft is shrinking and at the same time is crowded with competitors. Thus, it is unlikely that a U.S. manufacturer would undertake an initiative to attempt to compete for this market.

The market for future deliveries of 80- to 125-passenger jet aircraft is significant and may represent an opportunity for U.S. manufacturers to reenter the regional market. However, the only small U.S.-built jet, the 115-passenger Boeing 737-500, has not yet been sold to a regional airline.

### **The Rotorcraft Market**

Civil rotorcraft are operated today in a number of fields: energy, news, agriculture, executive transport, business, public service, police, and firefighting. There are currently 4,232 turbine-powered and 3,244 piston-powered helicopters in the civil fleet. Few helicopters operate as commuter carriers today, primarily because of the high operating costs. Scheduled passenger operations have been successful only where geographic barriers and lack of airports prevent ground transportation or fixed-wing aircraft from operating effectively. Still, a steady growth of civil helicopter markets is projected.<sup>9</sup>

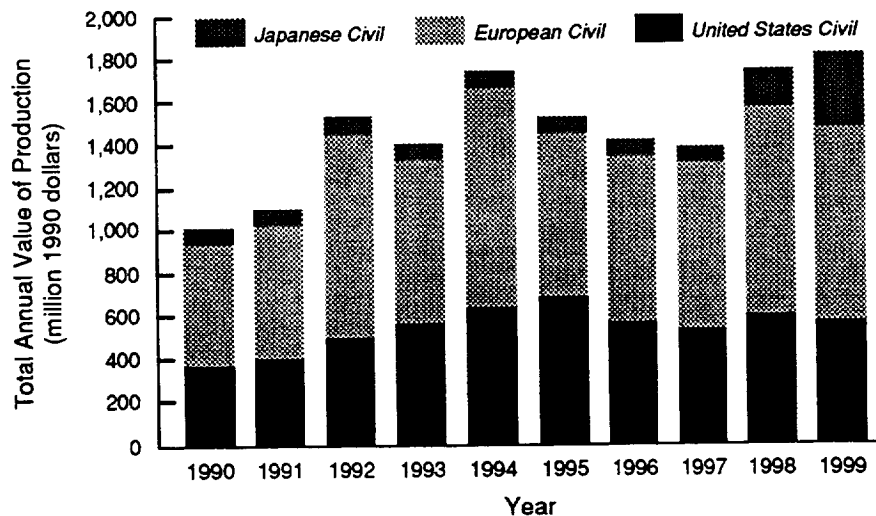
The value of the worldwide civil helicopter production in 1990 was \$1.0 billion and is projected to grow at an average rate of about 7 percent annually (Figure 4-2). This growth would result in a \$2 billion civil rotorcraft market by 2001, not including advanced vertical takeoff and landing (VTOL) aircraft such as the tiltrotor. Of the total world helicopter production, including military, the civil sector accounted for 17 percent in 1990 and is projected to account for 25 percent by 2001.

U.S. manufacturers delivered 570 civil helicopters in 1990, with a value of \$350 million (34 percent of the worldwide market). As shown in Figure 4-2, U.S. market share is projected to increase through the mid-1990s and then to decline to approximately 30 percent by the end of the decade.

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<sup>9</sup> National Research Council. 1991. *Worldwide Civil Helicopter Forecast by Weight Class*. Washington, D.C.: National Academy Press.





Source: Forecast International

FIGURE 4-2 World civil rotorcraft production forecast.

Recent U.S. helicopter exports, including military, have been in the \$300 million to \$400 million range annually. They are expected to increase to about \$700 million annually by the mid-1990s, due in part to increased export of civil helicopters.

Most civil helicopters, especially medium- and large-sized craft, are derivatives of military aircraft. There is only one new U.S. military development program in sight, a light attack helicopter, the Boeing/Sikorsky RAH-66 Comanche. European governments are proceeding with the development of an entirely new generation of military and commercial helicopters, which will cut heavily into U.S. market share in the late 1990s and after the turn of the century.

Civil, as well as military, helicopter programs are funded by governments in Europe. Recently announced European procurement plans include more than 1,000 20–30-passenger machines (military NH90s and EH-101s). A German company MBB has announced the production of the BO-108, an advanced composite light twin-turbine helicopter. Aerospatiale, jointly with Singapore and China, is proceeding with a light single-turbine civil helicopter, the P-120 L. The Eurocopter Tiger attack helicopter made its first flight in April 1991; 430 production units are planned. The BO-108 and P-120 will penetrate the lower end of the market, whereas civil versions of the NH-90, EH-101, and Tiger helicopters will fill market needs for intermediate- and large-size helicopters.

Eurocopter is a French/German company resulting from spin-off and merger during 1991 of the helicopter divisions of Aerospatiale and MBB. Dornier's helicopter activities will be included in Eurocopter after 1994. With the merger, Eurocopter has essentially a complete line of civil helicopter products. In addition to the Eurocopter merger, there is an increasing trend

toward international collaboration in the development of new rotorcraft, as illustrated in Table 4-2.

The civil helicopter market should continue to grow at a substantial rate beyond the \$2 billion level early in the next century. European and Japanese competition is intensifying rapidly with the formation of consortia, mergers, and government-funded development programs. U.S. industry will require very substantial research and development support if it is to remain technologically competitive and obtain a significant share of the civil helicopter market after the year 2000.

One rotorcraft area in which the United States has a significant lead is the tiltrotor, with a good technology base provided by the successful XV-15 research program and the V-22 military development project. Additional research, technology development, and system studies are needed to address the remaining questions regarding civil application of tiltrotor aircraft. If this effort provides positive results relative to the basic technical, environmental, operational, and economic issues, a major opportunity should develop for U.S. industry.

### **The General Aviation Market**

General aviation consists of the civil fixed-wing fleet, including business jets but excluding scheduled air carriers and noncertificated types. Thus, general aviation aircraft range from two-place trainers to wide-body turboprops used in business. The current U.S. GA fleet exceeds 200,000 airplanes for a variety of business and personal uses.

As shown in Figure 4-3, the GA manufacturing industry was devastated during the 1980s. From a peak of nearly 18,000 units in 1978, which were mainly personal aircraft, U.S. production declined to less than 1,100 units in 1987. During 1990, only 1,144 GA airplanes were produced in the United States. The turbine-powered business aircraft manufacturing sector recovered somewhat in recent years (449 turbine units in 1990 versus 372 in 1986). However, current production is less than half the number of units in the peak years 1978-1981. The piston powered sector remains depressed, with only 705 units produced in 1990, or about 5 percent the production of the peak years 1977-1979. Revenues of GA manufacturers did not drop as drastically as did the number of units produced because of the increased prices and production of a larger portion of more expensive models. Unpredictable costs of product liability, totally unrelated to product safety (Figure 4-4), have caused many manufacturers to cease production of light aircraft and their component parts.

European manufacturers are strong competitors in the business jet sector. They are expanding into the light aircraft sector previously dominated by U.S. manufacturers.

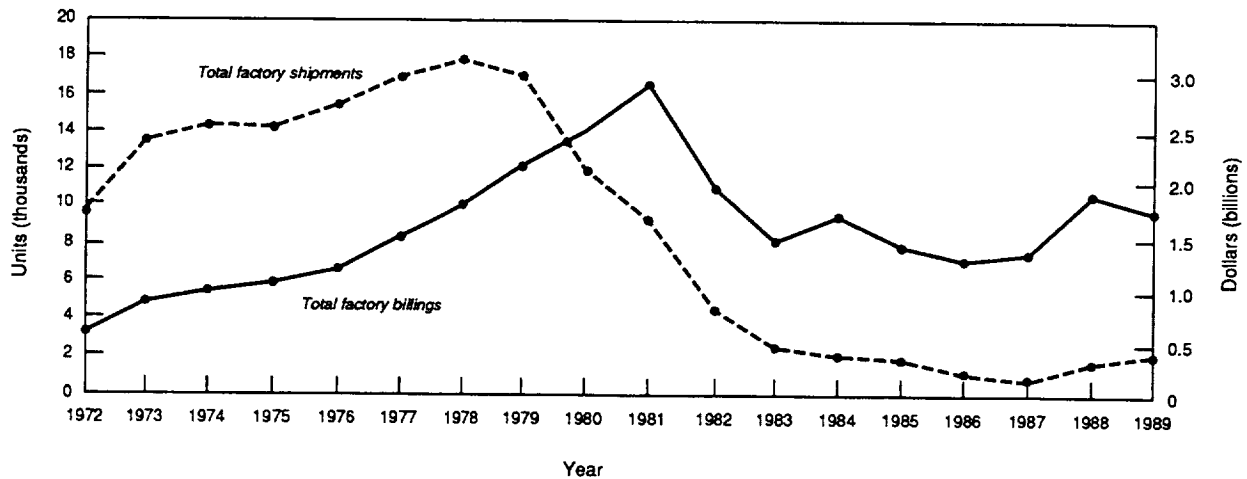
Notwithstanding increasing costs and complexity of operation in the national airspace system, utilization of general aviation airplanes has remained relatively strong. Following a 15 percent drop in the early 1980s, total annual flight hours by piston airplanes has remained level at approximately 27 million. Total flight hours for the general aviation turbine fleet increased steadily during the 1980s at a rate of about 4 percent per year, to approximately 5 million hours in 1990.

TABLE 4-2 International Consortia for New Helicopters and VTOL Aircraft

Aircraft	U.S.	U.K.	France	Germany	Italy	C.I.S.	Holland	Spain	Japan	China	India	Singapore
TW 68: 4-engine tilt wing VTOL, 12,000lb, 8-14 passengers									✓			
UROFAR: 30-passenger tiltrotor transport		✓	✓	✓	✓			✓				
AI29/T800: LH-engine- powered Mangusta antitank helicopter	✓				✓							
Battlefield Lynx: LH-engine powered Westland helicopter	✓	✓										
EH-101: large, multiengine, civil and military transport helicopter		✓			✓							
NH-90: medium tactical and transport helicopter			✓	✓	✓		✓					
Tiger: combat helicopter		✓*	✓	✓								
Advanced light helicopter 14-passenger transport				✓							✓	
BK-117: Turbomeca Artiel-powered utility helicopter			✓	✓					✓			
PI20L: five place executive helicopter			✓							✓		✓
Rolls-Royce-powered Kamov Ka-62R helicopter		✓				✓						

Source: American Helicopter Society

\*British Army Combat Helicopter Competition, only.



Source: General Aviation Manufacturers Association

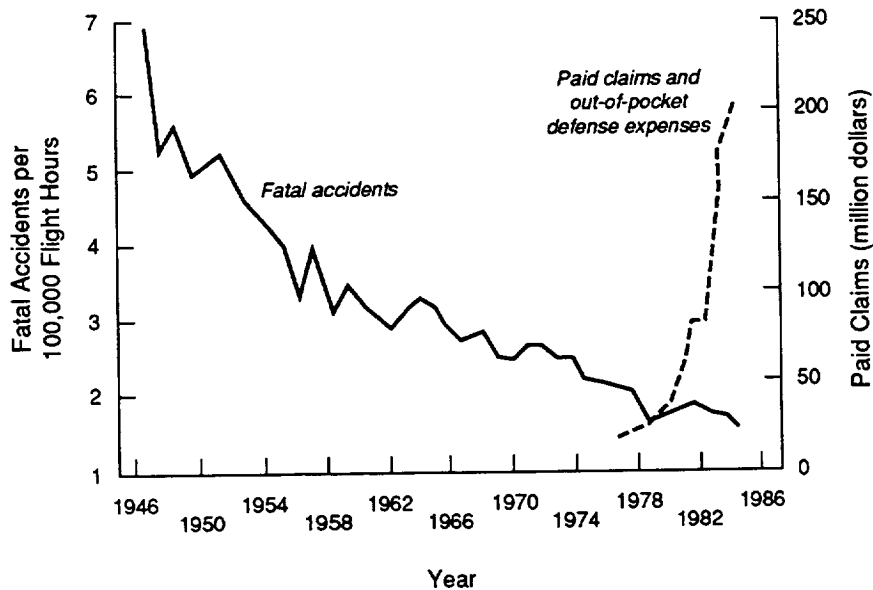
FIGURE 4-3 General aviation unit shipments/billings.

However, the general aviation fleet is aging rapidly. Currently the average ages of active airplanes are 14 years for turbojets, turboprops, and turboprops; 25 years for piston, single-engine aircraft; and 22 years for piston, multiengine aircraft. Given these average ages, the refurbishment and upgrading of equipment in the older airplanes have become major activities for maintenance organizations.

General aviation manufacturers have depended primarily on NASA and other elements of the aircraft manufacturing industry for technology input. The application of advanced technology in general aviation varies widely with category, with the largest application in turbine powered airplanes. The installation of relatively low-cost advanced avionics in older airplanes, as well as new, is significantly improving the usefulness of the GA fleet. Progress in the application of technology advancements in other areas has been slow in piston-powered types, where utilization of advanced technology is sharply controlled by considerations of cost versus benefit. In contrast, turbine-powered business aircraft designs have incorporated advanced technology to a fairly high degree and have even provided the first production application of some advancements.

## MARKET FORECAST

The growing population and the increasing demand for air transportation of people and goods are projected to continue the need for expansion of short-haul air transport in all categories. The need for short-haul service is increased further by mounting pressures to decentralize industry and population from troubled urban centers where it is costly to operate.



Source: General Aviation Manufacturers Association

FIGURE 4-4 General aviation fatal accidents and paid claims.

Because of congestion at busy hub airports, there is a developing need for air service between smaller communities that bypasses congested hubs. There also remains an unfulfilled need for efficient VTOL transport, both for interconnection with long range air service and for direct city-center to city-center transportation.

The developing congestion of the airspace and airport system at busy hub areas needs to be addressed with new and emerging technologies to bring about a quantum improvement in the efficiency and capacity of the system.

These needs, and many others, provide great opportunities for the development and application of advanced aeronautical technologies by NASA and U.S. manufacturers.

### Forecast for Commuter Aircraft

The commuter market is projected to remain the fastest-growing portion of U.S. airline traffic. Foreign manufacturers are expected to continue to dominate the supply of commuter airplanes for more than 20 passengers, unless the structure and requirements of the regional carriers change significantly. U.S. equipment and engine makers will continue to supply their products to international manufacturers. However, competition from subsidized foreign manufacturers will probably make the development and production of current-technology turboprop transports in the 20- to 50-passenger range economically unattractive to U.S. manufacturers.

Several factors are present that may offer new or expanded opportunities for the application of U.S. technologies to the commuter aircraft area. There appears to be a sizable market developing for 50- to 100-passenger turbofan commuter aircraft, primarily for use in "hub bypass" operations. Larger, faster, and more comfortable aircraft are needed for routes with longer stage lengths and higher traffic density. If advanced U.S. technology is made available for commuter airplanes and high bypass ratio turbofan engines, it appears likely that good opportunities could exist for U.S. industry.

Continued growth of traffic congestion at the major hubs will serve to limit growth of commuter airline traffic unless actions are taken to significantly improve both air- and ground-side systems. Satellite-based navigation and communication systems, combined with advanced ground and airborne computers, have great potential for improving the capacity and safety of the traffic system in terminal areas, en route, and on the ground. Implementation of these systems will be a major factor enabling orderly growth of the commuter airline market. Such growth is essential to meet national transportation needs, and with it will come opportunities for application of advanced technologies by U.S. manufacturers of engines, equipment, and hopefully, complete aircraft.

Integrating VTOL operations into existing airports, by the use of helicopters and tiltrotors has the potential to reduce commuter traffic on congested runways and on approach and departure paths, thus increasing the capacity of these airports. Rotorcraft also have the potential of providing hub bypass commuter operations in dense traffic areas. Key to realizing the potential of advanced rotorcraft in commuter applications is demonstration of the technology, environmental and passenger acceptability, operational suitability, and economics. Such demonstration is necessary to convince manufacturers and operators of the viability of commuter rotorcraft operations. The potential of advanced VTOL aircraft in commuter operations and other sectors of the air transportation system is discussed in more detail in the next section.

### **Forecast for Rotorcraft**

Civil use of rotorcraft is presently limited by external noise constraints, operating costs, lack of public heliports and associated ATM systems, and the perception that rotorcraft are less safe than conventional aircraft. U.S. industry is heavily challenged by foreign manufacturers and is losing market share to that challenge. However, on the demand side, there are several promising potential opportunities for application of advanced rotorcraft.

Recent studies conducted by NASA and the FAA show a potentially large market for tiltrotor aircraft. Major markets include "urban area to urban area" and "high-density hub feeder." Realization of these markets would require the total system and infrastructure for such operations to be developed, including the ability to operate separately from fixed-wing traffic, into vertiports located near populated areas, with acceptable noise, economics, passenger acceptance, and safety. The United States currently has a substantial lead in the development of tiltrotors for military use.

As mentioned in the previous section, advanced rotorcraft offer the potential for making a major contribution to the commuter sector and reducing congestion at busy hubs. A significant

contribution should be possible even without a whole new complex of vertiports and large improvements in external noise required for public acceptance of new vertiports. In addition, rotorcraft offer the promise of relieving the congestion of ground transportation feeding airports in major urban areas, both by providing air access to the hub from surrounding communities and by providing a route structure that bypasses the hub for travel from communities in the hub region to spoke destinations.

Demand for the unique capabilities of rotorcraft in a variety of mercy missions continues to increase. A new concept, now in the earliest discussion stage, stems from the need for a massive international disaster response capability, with both long-range and VTOL short-range airlift capability. Currently and in the near term, military agencies of the major powers will provide air transport resources for disaster relief. In the longer term, it appears that a vertical lift disaster relief force built around air-transportable, advanced rotorcraft could provide major advancement in international disaster relief.

Opportunities for research and technology development that can contribute to fulfillment of the needs for improved rotorcraft capabilities include (1) vibration and noise reduction; (2) improved productivity and reduced operating costs; and (3) development of satellite-based navigation, communication, and control systems. This includes the accompanying rotorcraft control systems and techniques that will allow safe operation of rotorcraft, independent of fixed-wing traffic. This technology is necessary to allow exploitation of the rotorcraft's vertical takeoff and landing capability in all-weather operations from nonrunway-type facilities, and it will improve both utility and safety.

### **Forecast for General Aviation Aircraft**

Continuing long-term growth in the use of GA airplanes in corporate and utility applications is projected by the FAA. The agency predicts a 50 percent increase in turbine-powered GA flight activity over the next 12 years. For piston-powered airplanes the FAA predicts that flight activity will remain level over the next 12 years.

Increasing problems with the infrastructure and quality of life for many people in major urban areas bring increasing pressures to decentralize industry and population. In the long term, this should stimulate a significant increase in the use of GA airplanes to provide the necessary point-to-point, on-demand air transportation for outlying communities and dispersed businesses and industries.

A large increase in the need for GA airplanes for training purposes is expected to continue. This increase results from the demand for new pilots caused by continued growth of the scheduled air carriers, the retirement of large numbers of pilots during the 1990s, and a reduction in the supply of pilots from the military services.

As discussed above, a number of factors constrained the growth of GA aircraft operations and caused a decrease in personal aircraft operations in the early 1980s. If these constraining factors were effectively addressed, general aviation could make an increasingly important contribution to the national transportation system. Improvement in the health and growth of GA

flight operations should reflect directly on the manufacturing sector, especially in view of the need to replace the aging fleet.

An infusion of new technology could make a major part of the existing GA fleet obsolete. A significantly improved low-cost power plant to replace the piston engine is an example of the type of technology that could rejuvenate light aircraft design and manufacturing.

## **BARRIERS**

The Committee believes that the biggest barrier to meeting future needs for short-haul air transport is the complex and costly airspace and airport traffic management system. This problem is especially severe at busy hubs and is rapidly getting worse. However, each of the five areas of need defined in Chapter 1 is relevant to the advancement of short-haul aircraft (i.e., cost, environmental impact, safety, performance, and capacity). These issues are discussed in the following sections.

### **Barriers to Commuter Aircraft**

Profitability and the associated availability of capital were, for a long time, deterrents to growth of the commuter airline industry. In recent years these issues have been mitigated somewhat by mutually beneficial associations between commuter and major airlines. However, economic issues remain a major constraint on the application of advanced technology in commuter airplanes, and shortage of capital inhibits U.S. builders of such aircraft.

The rapid growth of both the major and the commuter airlines has resulted in increasingly serious congestion at the busiest hubs. The commuter system, which has served all of its constituents well by providing safe, reliable, high-frequency service between small communities and hubs, has now become a major part of a rapidly worsening national problem. Both the land-side and the air-side have become overly congested, partly as a result of the success of the commuter concept.

A commuter passenger requires the same parking space, the same driving space, and the same terminal facilities as other passengers. Commuter air operations require the same attention and the same airspace, and in some cases more time to fit into the system, whereas productivity in terms of passengers per airport operation is lower. Realization of the full potential contribution of commuter, to the national transportation system depends on finding a solution to the hub congestion problem.

Although environmental considerations are not a major factor with commuter aircraft as currently used, they are likely to be of increasing concern with the emergence of advanced rotorcraft as economical modes of transportation.

Relatively little work has been done on the human/machine interface (cognitive engineering) for the class of equipment utilized by the commuter industry. As cockpit technology moves ahead, a better understanding of this area is needed. The major source of commuter pilots is general aviation, and the transition from a simple airplane to a highly sophisticated cockpit is a radical change that must be eased as much as possible.



### **Barriers to Rotorcraft**

Before rotorcraft can be used to help solve the runway capacity problem by absorbing a significant part of the short-haul traffic, a number of serious barrier issues will have to be overcome.

The first of these is high operating cost. There are many contributors to the cost problem. The initial capital investment is large. Helicopters are expensive because production runs are small and development costs are high, partly because of the empirical, trial-and-error aspects of so much of the design and development process. Production is expensive because of the large number of complex parts and, again, because production runs are relatively small. Maintenance is also expensive because of the complexity and the flight-critical nature of so many highly stressed fatigue-loaded parts, which has always required very conservative "safe life" parts retirement. For missions of any significant range, relatively poor cruise lift-to-drag ratio results in limited payload fractions, and low cruise speed further decreases productivity. Convertible rotorcraft, such as the tiltrotor, can improve the lift-to-drag ratio and cruise speed, and reduce the fatigue loading of components. However, with current technology the higher empty weight fraction of tiltrotors tends to erode part of the benefit.

Rotorcraft must justify their higher operating costs by operating from convenient, close-in vertiports. Community acceptance is a critical vertiport consideration, and noise is a major problem. Even with current technology, noise can be reduced by designing for lower tip speeds and lower disk loadings, but this further penalizes efficiency and productivity. Steep-gradient curvilinear operations can reduce the noise footprint considerably and help avoid noise-sensitive areas, but this introduces instrument flight rules, flight path control, and ATM system challenges. Because rotorcraft will probably want to take advantage of unused low-altitude airspace in congested urban areas, cruise noise is also an important issue. It is evident that the rotorcraft commuter problem must be attacked on many technical fronts.

The public perception of safety risks continues to serve as a barrier to both passenger acceptance of rotorcraft and acceptance by potential vertiport neighbors. The safety record of commercial passenger helicopter operators compares well with commuters, especially on the basis of accidents per departure. However, the fact remains that the safety record, as well as the perception of it, must be improved before broad public acceptance can be expected.

Another potential barrier to passenger acceptance is comfort. Current helicopter vibration levels, although greatly improved in modern designs, are still frequently well above the threshold of comfort, especially at high speed and during landing approach. Although the tiltrotor has a basic advantage in vibration over the helicopter at high speed, it still requires vibration control design and treatment to meet passenger acceptance standards. It is clear that abatement of internal noise, for both helicopters and rotorcraft, will require significant attention to new soundproofing techniques.

For trips of more than 150 miles, current modern helicopter cruise speeds (typically 150–160 knots) will probably be too slow for ready acceptance by the traveling public, whose expectations are based on higher fixed-wing speeds. The application of rotorcraft by commuter

airlines, other than for short trips, depends either on achieving a significant increase in helicopter cruise speed or on effective application of the tiltrotor.

### **Barriers to General Aviation Aircraft**

A number of issues form major impediments to realization of the opportunities provided by general aviation. These include price increases above the general rate of inflation caused by soaring product liability costs, loss of suppliers, changes in laws governing investment tax credits, weakening of the general economy, shortage of technical improvements, and the increasing complexity and cost of operation in the national airspace system. Each of these has in some way limited the growth of GA operations and drastically reduced the production of new aircraft.

### **NASA'S CONTRIBUTIONS TO SHORT-HAUL AIRCRAFT**

Short-haul aviation can benefit greatly from a broad-based NASA research and technology program in both the classical and the more exotic aeronautical disciplines. For the sake of clarity, the features of an effective program, as they pertain specifically to short-haul aircraft, are broken down into the categories of need described in Chapter 1. As mentioned there, these categories are not independent, they overlap to a significant degree, and technologies that contribute to furthering one need are likely also to further another. Table 4-3 shows the current (1992) funding for short-haul aircraft by discipline. As discussed in Chapter 1, the Committee was not constituted to recommend specific funding levels for the technologies discussed in this report. However, from the information shown in Table 4-2 and in Appendix C it is clear that NASA's emphasis in the short-haul aircraft category is on rotorcraft. In fact, of the \$32.0 million specifically devoted to this category, \$23.8 million was allocated to the rotorcraft research and technology base (see Appendix C) and \$5.2 million for "advanced rotorcraft technology." The remaining \$3.0 million was spent on propulsion technology for general aviation and commuter aircraft. Although the Committee believes that development and validation of rotorcraft technology is a worthwhile goal, and recognizes that much of the technology developed for larger subsonic aircraft will apply to commuter and general aviation aircraft, the nation would certainly benefit from a more balanced short-haul program. Better balance could be achieved through reallocation of a portion of rotorcraft funding to conventional takeoff and landing aircraft or, preferably, as part of an overall increase in the NASA civil aeronautics budget that keeps rotorcraft funding near current levels but increases funding for other short-haul aircraft.

Many of the advances that address these categories of needs are likely to be applicable to other categories of aircraft discussed in this report. In the experience of the Committee, broad-based technology development programs will tend to uncover applications in areas that were unforeseen at the beginning of the program. So, although consistent focus is needed to address the special needs of short-haul aircraft as one part of the total NASA program, care

TABLE 4-3 Short-Haul Funding by Discipline

Discipline	Current NASA Program (millions of 1992 dollars, percent of total) <sup>a,b</sup>	
Systems and operations <sup>c</sup>	\$5.9	18.4%
Aerodynamics	\$16.5	51.6%
Propulsion	\$3.0	9.4%
Structures and materials	\$3.3	10.3%
Controls, guidance, and human factors <sup>d</sup>	\$3.3	10.3%
<b>Total</b>	<b>\$32.0<sup>e</sup></b>	<b>100.0%</b>

Source: NASA Office of Aeronautics and Space Technology

<sup>a</sup> 1992 funding in real-year dollars, excluding fundamental research not tied to a specific application.

<sup>b</sup> Percentages may not add to 100% due to round off error.

<sup>c</sup> Includes both flight systems research and systems analysis studies.

<sup>d</sup> Includes the Avionics and Controls and Cognitive Engineering categories discussed in this report.

<sup>e</sup> Of the \$32.0 million total, \$29.0 million was devoted to rotorcraft technology and \$3.0 million to general aviation technology.

should be taken to ensure that the full range of applications of each technology is well understood.

### **Cost/Convenience**

Developing cost-effective aircraft is not necessarily the role of NASA. However, developing the technologies that lead to cost-effective aircraft is a proper role. Thus, development of a technology that promotes longer aircraft lifetimes, reduces engine fuel consumption, improves lift-to-drag ratios, reduces structural weight, or improves passenger comfort through reduction in noise or vibration levels can and should be undertaken by NASA.

**Research on continued airworthiness of aging aircraft, including aging characteristics of composite materials, inspection/nondestructive evaluation methods, and cognitive engineering, continues to be needed to make U.S. commuter aircraft commercially viable.** Practical alternatives to arbitrary life limits are essential for older commuter airplanes, which were designed to airworthiness standards that are now obsolete.

Improvement is needed in predictive analysis and model test techniques to increase the efficiency of the rotorcraft development process and thereby reduce acquisition cost. Also, to produce simpler designs that are cheaper to build and maintain, NASA's support is needed for

development of design concepts that take advantage of new materials, especially composites, to replace bearings with flexures and to tailor rotor blade dynamic characteristics.

Increased confidence is needed in definition of life cycle costs of new technologies, such as the tiltrotor, before the regional airline industry can be expected to invest in them. **The Committee believes that NASA can help build this confidence by validation of the critical technologies to minimize risk and by sponsorship of, and participation in, comprehensive system studies to define the total system and its technical and economic characteristics.**

Research and technology development is needed to improve rotorcraft passenger comfort. Primary areas in which NASA effort is necessary are vibration prediction methods, vibration reduction concept development, machinery noise reduction and suppression, and gust alleviation.

### **System Capacity**

Although the administration of the national airspace system is primarily the province of the FAA, the Committee believes that NASA has capabilities that could augment and complement those of the FAA. Thus, NASA can make a major contribution to increasing the capacity and efficiency of the system by developing technology that reduces the complexity and cost of access to that system. Advancements are badly needed, not just by the short-haul segment but by all users of the airspace system. **Areas in which NASA can provide significant contributions are: position determination and flight path guidance; traffic awareness and collision avoidance, both in the air and on the ground; and availability of real-time weather information for the flight crew.**

Advancements in computational capabilities and the maturation of new technologies such as satellite navigation, advanced Doppler radar, and satellite communications can be applied to provide a quantum improvement in the system. Significant cost and reliability improvements should be possible by automating many functions that are currently very labor intensive.

**The Committee also believes that a study is needed to establish the degree to which existing airport capacity could be increased by shifting some short-haul traffic to helicopters and tiltrotors, and having vertiports integrated into available airport real estate.**

### **Environment**

The emissions that are generated by rotorcraft, general aviation, or even commuter aircraft are minimal compared to those generated by large subsonic transports or potential supersonic transports. The primary impact of short-haul aircraft on the environment then is the generation of noise. **The Committee believes that NASA's excellent capabilities in acoustics should be applied to reducing both exterior and interior noise of rotorcraft, GA, and commuter aircraft. This effort should be an essential part of a comprehensive noise research and technology development program, including research in the fundamentals of noise phenomena and the development of improved noise prediction methods; development and substantiation of technologies for reducing engine, rotor, and propeller noise; research on human response to noise and development of noise measurement criteria; research and**

**technology for active control of noise; and development of U.S. capabilities for large-scale acoustic wind tunnel testing.** Furthermore, to help reduce terminal area noise and maximize the utility of rotorcraft, there is a need to develop operations-enhancing technologies such as steep-gradient curvilinear instrument flight rules approach guidance systems, ATM system integration techniques, and improved pilot/vehicle interfaces.

### Safety

Because flight crew error continues to be the primary cause of fatal accidents and addressing this cause can potentially make the largest contribution to short-haul aviation safety, **NASA should undertake an aggressive safety research program, focused on cognitive engineering, and should address the features that are unique to the operation of commuter, rotorcraft, and general aviation aircraft.**

In addition, the development of fail-safe designs, integrity monitoring systems, and damage-tolerant gears and shafts for on-condition removal are needed to reduce maintenance costs and increase the safety of rotorcraft. Particularly challenging is the need for a real-time condition monitor for metallic rotating structural elements. Acoustics emissions and laser information transfer offer intriguing possibilities in this area.

NASA has unique capabilities and facilities and can make a significant contribution to GA safety in the future, as it has in the past. Research and technology development in GA safety should be rejuvenated at NASA. Some of the items that should be included are cognitive engineering, flying qualities, departure from controlled flight, and spinning.

Another major contribution needed from NASA toward general aviation safety is the development of the basic technology for advanced low-cost on-board systems, including flight path guidance and control, information transfer, traffic awareness and collision avoidance, and real-time weather presentation. Application of these technologies, in combination with a greatly improved airspace management system, could bring about a dramatic improvement in the usefulness and efficiency of general aviation operations.

Finally, the Committee believes that **NASA's capabilities in simulation and training could help enhance the initial training and skill maintenance programs of all aircraft pilots and mechanics.** Emerging computation and simulation technologies could provide the basis for low-cost personal training aids and simulators that could aid in keeping more sophisticated aircraft well maintained and help alleviate the primary factor in GA, rotorcraft, and commuter accidents—pilot error.

### Aircraft Performance

All categories of short-haul aircraft can benefit from advances in performance. NASA's role as the primary provider of advances in the traditional aeronautical disciplines (propulsion, aerodynamics, materials and structures) will continue to provide incremental improvement in the speed, range, and payload of short-haul aircraft. Furthermore, it can be expected that NASA will play a major role in advancing the more exotic technologies associated with cognitive

engineering, and advanced avionics. Each category of aircraft considered in this section will require advances in performance to remain viable in future markets.

In particular, it is the belief of the Committee that *NASA's very extensive capabilities should be applied toward major improvements in rotorcraft speed and efficiency*. The research and technology effort should range from studies of improved aerodynamics, dynamics, materials, structures, and machinery, to investigation of promising new VTOL configurations.

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**PART III:**  
**TECHNICAL DISCIPLINES**





## ENVIRONMENTAL ISSUES

### INTRODUCTION

The future operation of all aircraft classes will be constrained by requirements to reduce their environmental impact. These constraints include a complex system of restrictions on both noise and ozone-depleting or ozone-generating emissions. It is a proper role for the National Aeronautics and Space Administration (NASA) to attack these issues because of the effects that noise, smog, ozone depletion, and sonic booms have on the quality of life around airports and major cities. It should also be noted that many of the aircraft that are being designed today will still be in production 20 years from now and may still be in operation as much as 30 years from now. Without significant effort to make U.S.-built aircraft less intrusive, substantial opportunity for market growth may be forfeited. Throughout this report the Committee has stressed the need for NASA to be more involved in helping industry meet this type of challenge. Thus, NASA, the U.S. aircraft industry, and the Federal Aviation Administration (FAA) as well, must find a way to work together to address these national and international constraints to ensure that U.S. aircraft remain competitive into the next century, and to avoid increasing the adverse effects that aircraft have on the quality of life of the citizens of the United States and the world.

This chapter discusses the issues involved in reducing the impact of aircraft, and offers a number of recommendations to focus NASA's ongoing noise and atmospheric research programs to address these problems. The boxed material summarizes the primary recommendations that appear throughout the chapter, with specific recommendations given in order of priority, and the benefits that can be gained through research and development aimed at the environmental compatibility of aircraft.

### EMISSIONS

Much has been said and written about the atmospheric effects of fossil fuels. However, the lack of sufficiently accurate analytical models does not permit detailed definitions of acceptable emissions. Rather, the best that can be hoped for is setting of reasonable goals for

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## Recommendations

### General

NASA, the U.S. aircraft industry, and the FAA must work together to address national and international environmental concerns both to help the United States gain a competitive edge and to avoid increasing the adverse environmental effects of aircraft on the ground and in flight.

### Specific

1. Current and proposed research programs sponsored by NASA should be continued to enhance understanding of the impact of engine emissions on atmospheric ozone.
    - It is imperative that improved modeling, data collection, and verification of models of the chemistry and dynamics of the troposphere also be included in NASA's long-term subsonic aircraft program.
    - NASA is strongly encouraged to investigate worst-case scenarios for stratospheric ozone depletion to establish a basis for reasonable regulation aircraft emissions and to begin developing engineering solutions.
    - To enable a successful commercial HSCT fleet, NASA must continue or accelerate aggressive programs in advanced emission reduction technology related to the chemistry and dynamics of the stratosphere.
  2. NASA's aggressive research and development program for aircraft noise reduction must include HSCT jet engine noise suppression, subsonic engine fan noise suppression, airframe noise reduction, and noise abatement flight operations.
  3. NASA should continue its research and development program in sonic boom reduction for HSCT.
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reducing emissions that can be worked toward until research into the basic chemistry and dynamics of the atmosphere can yield a more definitive answer. Thus, the Committee believes that a two-pronged attack should be mounted: **current and proposed research programs sponsored by NASA, as well as the National Science Foundation, Environmental Protection Agency, National Oceanic and Atmospheric Administration, and the Department of Energy, should be continued to enhance understanding of the impact of engine emissions on the atmosphere.** While that research is being performed, aircraft designers should be aggressive in their efforts to reduce emissions from all categories of aircraft. In particular, **NASA is strongly encouraged to investigate worst-case scenarios for stratospheric ozone depletion from high-speed civil transport (HSCT) to establish a basis for reasonable regulation of aircraft emissions, and to begin developing engineering solutions.** For example, an emission

**Benefits of Research and Technology Development in Aircraft Environmental Compatibility****Emissions**

- Enhanced understanding of atmospheric effects of emissions
- Realistic regulations for emissions
- Better analytical modeling of atmospheric effects
- Design solutions

**Noise**

- Reduced airport/community noise
- Possibility of acceptable sonic boom for HSCT
- Design solutions

index of 3–5 g of nitrogen oxide ( $\text{NO}_x$ ) per kg of fuel burned for a commercial HSCT fleet operating in a cruise mode in the stratosphere (15–30 km) would represent a reduction by a factor of 10 over existing engine combustion technology. This magnitude of reduction can be used as a guide for designers as researchers work toward more precise definition of the limits.

Much is known about ozone depletion. It is clear that an HSCT, which will fly higher in the stratosphere and thus closer to the ozone layer, will have a more profound effect on ozone depletion than lower-flying aircraft. Furthermore, an HSCT will burn more fuel per seat-mile than a corresponding subsonic aircraft. These problems can be alleviated somewhat by improving (lowering) the  $\text{NO}_x$  emission index of HSCT engines or by flying at lower altitudes at correspondingly lower Mach numbers. **To enable a successful commercial HSCT fleet, NASA must continue or accelerate aggressive programs in advanced emission reduction technology related to the chemistry and dynamics of the stratosphere.**

The corresponding problem for aircraft that fly in lower levels of the atmosphere is generation of noxious emissions that contribute to ozone depletion, but also produce smog, affect atmospheric oxidation (cleansing of the atmosphere), and contribute to global warming. Finally, at both takeoff and landing, emissions of  $\text{NO}_x$  can increase smog and ozone near the ground. Thus, **it is imperative that improved modeling, data collection, and verification of models of the chemistry and dynamics of the troposphere and tropopause also be included in NASA's long-term subsonic aircraft program.**

**NOISE**

Development of future aircraft of all classes must consider both U.S. and international noise standards. Hence, there are two interrelated challenges. **The FAA, NASA, and other federal agencies must effectively represent the interests of the U.S. public, as well as the U.S. aircraft and airline industries, in the development of international noise standards.**

Also, **NASA must maintain a very aggressive noise reduction program to ensure the existence of technology that will enable U.S. aircraft to meet international noise standards while operating on a sound fiscal basis.**

Noise standards (FAR-36)<sup>1</sup> exist for current short-haul, general aviation, and subsonic aircraft, but not specifically for the HSCT. Standards for subsonic aircraft are divided into three classifications depending on the date of the certification application, with Stage 3 designating the most quiet aircraft. Aircraft that meet Stage 3 noise limits have provided substantial noise reductions relative to older aircraft. Nevertheless, many airports impose additional noise restrictions that penalize payload or range by requiring operations at reduced takeoff weight or prohibit night operations. It is clear that pressure to further reduce noise will continue to increase.

An aggressive noise reduction research program for advanced subsonic aircraft should be aimed at achieving Stage 3 minus 10 dB. Increased bypass ratio engines with advanced fan noise reduction are critical, and full achievement will require airframe noise reduction as well. The accepted noise goal for future HSCT aircraft is to be certified to a standard equivalent to the Stage 3 limitations that subsonic aircraft are subject to. This will require HSCT engines to be 10–20 dB quieter than unsuppressed low bypass ratio turbofan or turbojet engines. Although in recent years there has been considerable progress toward the HSCT goal with advanced suppressor designs and advanced engine cycle selection, a considerable challenge remains. The level of jet noise suppression achievable is the critical element, and considerable development is necessary.

Required future reductions in advanced subsonic and HSCT system noise will require significant reductions in engine and airframe noise. Aircraft operations can have an impact on noise footprint by trading between airport noise and community noise. Advances in the air traffic management (ATM) system, flight operations, and smart aircraft controls are enhancing elements in producing the tradeoffs.

Noise levels inside current subsonic and supersonic aircraft that passengers and crew are exposed to are not as comfortable as they should be. This is an area in which U.S. aircraft could gain a clear competitive advantage over foreign competitors.

Concerted and continuing efforts are required to significantly reduce noise. NASA should lead the basic research to substantially improve the sophistication and technical strength of noise analysis and design computational tools. It should also lead in the development of new noise reduction concepts. **NASA must maintain an aggressive research and development program in aircraft noise reduction that includes the following elements:**

- **Conduct and sponsor fundamental research to understand and reduce high-speed jet and turbomachinery noise.**
- **Conduct and sponsor fundamental research to understand human response to noise and vibration in aircraft cabins, flight decks, and crew rest areas.**

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<sup>1</sup> Federal Aviation Regulation (FAR).

- **Develop technology for predicting and measuring long-range ground-to-ground and flight-to-ground sound propagation for airport and en route noise assessment.**
- **Develop technology for prediction and control of vibroacoustic responses of aircraft structure and materials.**
- **Develop experimental techniques and facilities to permit acquisition of accurate acoustic, aerodynamic/structural dynamic, and psychoacoustic data in support of aircraft acoustic technology development.**
- **Develop signal processing technology to improve analysis and utilization of data from acoustic wind tunnel testing.**

Unless the United States mounts concerted efforts to augment the development of advanced computational and experimental capabilities, it will not be possible to achieve technology parity with similar European efforts. In the absence of these acoustic research facility capabilities in the United States, our industry and government research and development efforts typically utilize foreign facilities. In order to compete, it is necessary for the United States to support the development of appropriate facilities.

## **SONIC BOOM**

Sonic boom disturbance produced by a conventional HSCT will make routine supersonic flight over land impossible. Thus, although a large potential market may exist for an aircraft that cruises supersonically over water and subsonically over land, the capability to fly supersonically over land would expand the market considerably and represent an important competitive edge. As is the case with emissions and noise standards, a U.S. response to sonic boom standards must enable the U.S. aircraft industry to remain competitive in international markets. Hence, **the U.S. response must include an integrated approach, with NASA, industry, and FAA participation.**

Reduction in the loudness of a sonic boom requires a reduction in maximum overpressure. Current configurations for large supersonic aircraft typically produce sonic booms having a maximum overpressure of 2-3 pounds per square foot (psf). Although alternate configurations show promise for overpressure levels below 2.0 psf, much research is still required.

The duration of the sonic boom also impacts loudness, but very little benefit is obtained by modification of aircraft configuration that influences sonic boom duration. In addition, modifications to the configuration that are great enough to have a significant impact on duration usually lead to other design penalties. Reduction of the size and shape of the initial shock (shock front) will also reduce the loudness of the sonic boom.

**The Committee strongly encourages NASA to continue its intensive and aggressive research and development program in sonic boom reduction. This program should include the following components:**

- **development of sonic boom exposure criteria needed to assess the potential of acceptable supersonic flight over land;**
- **sonic boom propagation studies to better predict environmental (temperature, typography) influence on sonic boom impact; and**
- **development of analysis and design methodologies required to produce aircraft configurations that generate sonic boom having minimized impact.**

The NASA program should reflect a balance between the pursuit of overland supersonic flight and optimized designs for mixed subsonic/supersonic operations. Given the various international parameters, it is in the best interest of the U.S. aircraft industry for NASA to pursue optimized designs for mixed operations, while developing technology for supersonic flight over land at a lower priority.

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## 6

### OPERATIONAL ISSUES

#### INTRODUCTION

The Committee is aware that there are increasingly serious constraints on the movement of all classes of aircraft at many U.S. airports. This condition is spreading rapidly to Europe and the Far East. These constraints can be described as congestion—the problem of trying to fit more and more aircraft into the same amount of space. Defined more broadly, the problem lies in the limited capacity of airports to accommodate aircraft on the ground, the limited capacity of the air traffic management (ATM) system to accommodate aircraft in the air, and the difficulties in integrating the two. A recent report by the Transportation Research Board of the National Research Council<sup>1</sup> outlined seven alternative strategies for accomplishing long-term increases in capacity at the nation's airports. These range from incremental improvements of existing systems to complete reconfiguration of the current systems to incorporate advanced management techniques and technology. Although the Committee on Aeronautical Technologies was not constituted to investigate these issues in detail and was not chartered to recommend specific approaches, it is clear that opportunities to expand existing facilities will be severely limited in the future. One possible approach for addressing the problem of congestion over the long term is through the application of advanced technology to develop new airport and ATM systems. This approach concurs with the Transportation Research Board recommendation for a coordinated approach that includes expansion of current facilities over the short term and incorporation of advanced systems over the long term. This brief chapter discusses in more detail the issues of capacity and congestion as they relate to airport systems and to current and future ATM systems. The boxed material summarizes the primary recommendations that appear throughout the chapter, with specific recommendations given in order of priority, and the benefits that can be gained through research and development aimed at aircraft operations.

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<sup>1</sup> National Research Council. 1990. Airport System — Strategic Choices (Transportation Research Board Special Report 226). Washington, D.C.: National Academy Press. 1990.

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### Recommendations

#### General

Coordinated activity should be undertaken between NASA and the FAA to significantly increase the capacity of the worldwide aviation system, beginning with the U.S. domestic ATM system.

#### Specific

1. NASA should work with the FAA, the airlines, and aircraft manufacturers to bring about implementation of the Global Positioning System (GPS) for use in the ATM system as soon as possible.
  2. NASA should focus its efforts, in cooperation with the FAA and industry, to expedite
    - full integration of on-board communication, navigation, and flight management systems;
    - control and standardization of software for both on-board and ground-based computer systems;
    - development of a mission monitor to address any unacceptable developments that occur on board the aircraft, in the satellite system, or in the communication system, whether in flight or on the ground;
    - development of a satellite communication system along with a global infrastructure to ensure clear and redundant communications; and
    - refinement of inertial navigational systems, including the use of fiber optics.
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## AIRPORT CAPACITY

Every airport has a distinct personality profile consisting of runway/taxiway geometry, terminal/ramp configuration, usage by time of day, servicing facilities, noise and other environmental limitations, weather conditions, and user operational policies.

The most obvious solution to the ground congestion problem is more concrete (new airports, new runways, new taxiways, more ramp space), but this is expensive, time-consuming, and in many cases exceedingly difficult because of local objections to most forms of growth. Fortunately, considerable improvement is possible through simultaneous use of multiple runways, reducing aircraft separation on the runway, and more optimal routing of both aircraft and vehicular traffic on the ground. The Committee believes that implementation of the Global Positioning System (GPS) would greatly enhance runway and taxiway capacity. Clearly, the National Aeronautics and Space Administration (NASA) has a major role to play in this implementation and should work with the Federal Aviation Administration (FAA), the airlines, and aircraft manufacturers to bring it about as soon as possible. Furthermore, the Committee believes that an operations research program should be undertaken



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**Benefits of Research and Technology Development in Aircraft Operations****Air Traffic Management System and Airport Capacity**

- Optimal ground operations
- Reduced takeoff and landing separation
- Reduced aircraft separation in flight
- Integration of international ATM systems
- Reduced ATM system complexity
  - Greater on-board control
  - Integration of international ATM systems
  - ATM technology validation

**Safety**

- Reliable automated systems
- Enhanced communications
- Precise relative and inertial position fixing

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to evaluate and define each individual airport's problems. Such a program should include the development of a national data bank containing all factors unique to each airport, which would be monitored continuously to update and maximize the airport's efficiency. It is assumed that the FAA would be the primary sponsor of such an effort, but NASA should use its expertise in aeronautics to contribute wherever possible. This program could also provide clues regarding the best possible use of rotorcraft equipment in the discrete environment of each airport. With concentrated effort in this area, existing airports may not reach their ultimate capacity before 2000.

Although the Committee is concerned with airport terminal buildings and landside facilities, a literature review showed that previous work done by the National Research Council and others in this area, has been more than adequate. In particular, attention is directed to the *Workshop on Future Airport Passenger Terminals*.<sup>2</sup> That report outlined 15 needs for the future of airport terminals. In the opinion of the Committee, none of these fall within the province of NASA. However, it is clear that as NASA works with industry to develop new concepts for advanced subsonic aircraft and high-speed civil transports it must remain cognizant of the impact those designs have on the airport systems that must accommodate them.

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<sup>2</sup> National Research Council. 1989. Washington, D.C.: National Academy Press.

## AIR TRAFFIC MANAGEMENT SYSTEM

The current global airspace system is a severely fragmented conglomeration of national and international interests that have little in common. In spite of this, the system manages to successfully separate both en route and terminal traffic, thereby maintaining a remarkable safety record. However, several factors suggest that the present system will not be able to continue to cope successfully with the ever-increasing volume of traffic (both flights and passengers) that is forecast for the next 20 years. The emergence of Eastern Europe, Russia, China, and Southeast Asia as major contributors to airspace congestion, and the imposition of increasing environmental constraints dictate the need for a complete revision of the current system.

The lead time to accomplish this overwhelming task is very short; therefore, the technologies involved must be explored, proved, and implemented by the year 2000. The United States is in a position to assume the leadership in technology development that will set standards and methodology for the future; this opportunity must not be lost.

At least seven distinct and equally important issues must be addressed:

1. automation of traffic control and aircraft position prediction in real time;
2. establishment of digital data link (i.e., automatic altitude, heading, and speed logging);
3. direct access to on-board flight management computers for flight path guidance;
4. implementation of non-ground-based navigation, surveillance, and communication systems;
5. understanding of wake/vortex turbulence and its consequences;
6. provision for real-time weather information and analysis for use by the on-board flight guidance and navigation systems; and
7. development of provisions for rotorcraft to operate efficiently within the system.

Promptly and aggressively addressing these issues will ensure a continually improving safety record while at the same time increasing system capacity. In particular, implementation of the maximum practical global radar coverage would greatly reduce oceanic separation requirements, vastly increasing the capacity of that part of the system.

Considerable effort has been dedicated by both the FAA and NASA to all of these issues. Now, these efforts must be moved into the operational world in order to establish U.S. leadership of the global airspace system.

Taken as a whole, the seven issues listed above, when fully developed and implemented, will also lead to significant economic benefit to the worldwide transportation and aviation manufacturing industry, which will:

- increase the capacity of the global airspace system;
- save fuel and enhance safety, comfort, and the overall effectiveness of the ATM system by increasing the efficiency of flight path guidance;

- provide an opportunity to open more airports and more runways to all-weather operation;
- provide accurate real-time presentation and control of airport surface traffic;
- eliminate potentially dangerous uncontrolled commanded avoidance maneuvers; and
- provide a threshold for the entry of rotorcraft into the system.

The Committee has identified the following technologies that are needed for implementation of the global ATM system. **NASA should focus its efforts, in cooperation with the FAA and industry, to expedite:**

- **full integration of on-board communication, navigation, and flight management systems;**
- **control and standardization of software for both on-board and ground-based computer systems;**
- **development of a mission monitor to address any unacceptable developments that occur on board the aircraft, in the satellite system, or in the communication system, whether in flight or on the ground;**
- **development of a satellite communications system along with a global infrastructure to ensure clear and redundant communications; and**
- **refinement of inertial navigational systems, including the use of fiber optics.**



## AERODYNAMICS

### INTRODUCTION

Future progress in aeronautics will be based on the coupling of advanced tools with new understandings of fluid mechanics and interactions between the various aeronautical disciplines. New interdisciplinary computational tools and new experimental capabilities will play increasingly important roles in aeronautical technology progress. These new methods will profoundly affect the cost and speed of aircraft design processes as well as the efficiency and utility of future aircraft. This vision for the future of U.S. aeronautical technology can be realized only through investment in computational and experimental infrastructure and in the development and precompetitive validation of selected technologies. For the United States to compete more effectively in technology development in the future, science and engineering efforts that support industry must be reinvigorated. This reinvigoration will require an increased level of investment as well as careful assessment of investment strategy. A strong need exists to strengthen the weakest link in the technology development chain: namely, technology validation for risk minimization.

In recent years, the National Aeronautics and Space Administration (NASA) has recognized the importance of technology development needs for high-speed civil transports (HSCTs), advanced subsonic transports, and hypersonic vehicles of all types, as well as the need to maintain its facility capabilities through the Wind Tunnel Revitalization Program. In each of these areas, however, overall constraints have limited NASA's ability to establish the kind of aggressive research efforts needed to maintain U.S. competitiveness in aeronautics. This chapter charts a course for NASA, industry, and academia to pursue toward the specific aerodynamics goals needed to achieve competitiveness. The boxed material summarizes the primary recommendations that appear throughout the chapter, with specific recommendations given in order of priority, and the benefits that can be gained through aerodynamics research and development.

Although discussion of individual technical disciplines is facilitated by categorization, progress in technical fields is enhanced by an interdisciplinary approach rather than by the more traditional sequential application of various technical skills. In the past, the disciplines of

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### Recommendations

#### General

NASA must continue to provide the necessary resources for aerodynamics research and validation, including resources focused on specific key technologies, resources to maintain and enhance ground and flight test facilities, and resources for enhanced analytical and design capabilities.

#### Specific

The following research topics should serve as the focus of NASA's research effort in aerodynamics:

1. aerodynamic cruise performance, including subsonic and supersonic laminar flow control technology;
2. aircraft propulsion/airframe integration for both subsonic and supersonic aircraft;
3. low speed and high lift for subsonic configurations, including wake mechanics, wake vortex, and measurement technology;
4. computational fluid dynamics for aircraft design, including validation of codes;
5. low speed and high lift for supersonic configurations; and
6. aerodynamics of rotorcraft.

The following should be the focus of a program to enhance NASA's ground-based experimental facilities:

1. revitalization of existing facilities on an expedited basis;
2. establishment of an intensive program to develop high-resolution nonintrusive instrumentation;
3. fitting of the 40'  $\times$  80' tunnel at the Ames Research Center with acoustic lining;
4. development of a low-speed (Mach 0.1–0.5), low-disturbance test capability to operate at chord Reynolds numbers in excess of 50 million; and
5. research to examine the feasibility of a supersonic (Mach 2–6) low-disturbance test capability to operate at full-chord Reynolds numbers of 400 million to 500 million.

The following should be the focus of a program to enhance NASA's experimental flight facilities:

1. revitalization of flight research capability and in-flight technology validation efforts in all speed regimes; and
  2. development of advanced measurement technologies for flight research.
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aerodynamics, structures, and controls were largely exercised sequentially in the design process. Propulsion system analysis proceeded independently and was integrated later into the design. Such a process requires several cycles of iteration to converge on a suitable design, and

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**Benefits of Research and Technology Development in Aerodynamics****Aircraft Operations**

- Reduced fuel consumption
- Decreased cruise drag
- Increased climb and descent lift-to-drag ratios
- Reduced takeoff and landing noise

**Aircraft Design and Development**

- Shortened development cycle
  - Improved computational capabilities
  - Improved testing facilities
  - Technology validation
- 

consumed considerable time and money. Also, not only does this procedure not guarantee an optimum configuration satisfying multiple design constraints, it almost precludes such a configuration because the efforts devoted to the initial steps in the design process become progressively harder to change. In some cases, cost and time constraints preclude more than one or two iterations.

The increasing maturity of computational approaches in the various design disciplines provides new opportunities to couple the disciplines more tightly earlier in the design process. Routinely treating aerodynamics, structures, propulsion, and controls virtually simultaneously and continuously throughout each step of design has very large payoffs that fall into several categories. First of all, the resulting design is truly optimized and is, therefore, superior to those derived through the older, sequential approach. A second major payoff is a significant reduction in the time required to evolve a final design. Attainment of this goal is critical to the success of the transport aircraft industry.

NASA has recognized the potential advantages of multidisciplinary analyses and plans to focus considerable attention on this in the Computational Aerosciences portion of the national High Performance Computing and Communications program, which was initiated in fiscal year 1991. The goal for the 1990s is to develop the capability to computationally couple aerodynamics, structural response, propulsion system effects, and active controls into a single computation and to structure the resulting codes to take advantage of massively parallel computational system architectures that are expected to be in widespread use after the mid-1990s.

These NASA efforts are highly endorsed by the Committee and complement similar industry activities that will include manufacturing considerations in the trade-off decision-making process. The impact of rapid design processes that allow time for examining the trade-offs between various disciplines was evident in the design of the folding wing tip of the Boeing 777.

Three configuration options were examined: an external hinge, an internal hinge retaining the original wing surface contours, and an internal hinge with a local thickening of the wing. An early wind tunnel test provided some baseline aerodynamic information, but the subsequent design iterations and final design decisions were made rapidly by using computational fluid dynamics (CFD). A final verification wind tunnel test could be performed only after the design was frozen.

This use of computational aids is being extended into multidisciplinary analyses coupling aeroelastic effects with structural analyses. The use of CFD for preliminary aerodynamic load predictions early in an airplane development program will significantly shorten the development cycle. Use of CFD to permit flutter prediction early in the design process will reduce reliance on traditional after-the-fact remedies such as mass balancing.

Early in this study the Committee decided not to address the hypersonic flight regime and to set the upper limit of vehicle speeds to encompass the HSCT. This section of the report, therefore, does not address the aerodynamics of hypersonic flight. Before moving to the areas considered, however, some comments on the state of hypersonic research in the United States are appropriate.

Current U.S. capabilities in hypersonic research have their roots in research efforts that were concluded more than 20 years ago with the culmination of the X-15 program. Today, the nation's hypersonic capability is largely applied to the National Aerospace Plane (NASP) program, which is focused on the specific objective of the technologies necessary to design and build the X-30 aerospace plane capable of single stage to orbit. As a consequence, few resources are available for generic hypersonic research that does not support NASP.

The key aerodynamics technologies have been divided into the following categories, each of which is discussed in corresponding sections of this chapter:

- *Low speed and high lift for subsonic configurations:* This portion of the chapter examines the approach and takeoff flight phases for subsonic aircraft, encompassing high lift system performance in detail and overall takeoff and landing performance in general. Noise is included because this is the flight phase in which it is most troublesome.
- *Subsonic aircraft propulsion/airframe integration:* Aerodynamic interaction effects between a subsonic airframe and its propulsion system has significant effects on the economics of aircraft cruise performance. In addition, the integration must also recognize the need for low noise emission during takeoff and landing.
- *Aerodynamic cruise performance:* Efforts to maximize lift-to-drag ratio (L/D) and minimize cruise drag are critical to the economic success of most commercial aircraft. Lower drag relates directly to lower fuel costs and higher profits for the air carrier.
- *Low speed and high lift for supersonic configurations:* Supersonic aircraft shapes are strongly influenced by the need for economical supersonic cruise performance. Virtually all the design decisions to improve performance in this



flight phase have deleterious effects on the approach and takeoff flight performance. The requirements for improving the technology base for the design of supersonic aircraft are discussed in this section.

- **Supersonic aircraft propulsion/airframe integration:** The integration of the propulsion system with the airframe is a very important factor for all categories of aircraft. For supersonic designs in particular, aerodynamic interaction between the airframe and the propulsion system is a critical task, made more difficult by the need to minimize takeoff engine noise.
- **Aerodynamics of rotorcraft:** Aerodynamics of rotorcraft and tiltwing aircraft are especially complex, because they require investigations of exceptionally wide speed ranges and varying angles of airflow.
- **Test facilities:** The numerous new or updated flight and ground test facilities that will be required to accomplish various technical goals set forth in the report are discussed in this section. The use of computational tools and associated computers that can predict complex flow fields around aircraft in all speed ranges is also of growing importance. Specific applications of CFD are discussed in detail in the preceding categories, but this section of the chapter contains a more general summary.

A generally recognized and acceptable measure of aerodynamic efficiency is the lift-to-drag ratio. Table 7-1, prepared by the McDonnell Douglas Aircraft Company, lists subsonic L/D improvements achievable for the time period of this study if the recommendations in this chapter are implemented.

TABLE 7-1 Potential L/D Improvements

Application	Potential L/D Increase
Aspect ratio increase (11-17.5%)	15%
Laminar flow control (upper wing/tail surface)	10-12%
Airfoil development	2-3%
Turbulence control (fuselage/lower wing)	2-3%
Induced drag	3-4%
Total	~ 35%

Source: McDonnell Douglas Aircraft Company

## LOW SPEED AND HIGH LIFT FOR SUBSONIC CONFIGURATIONS

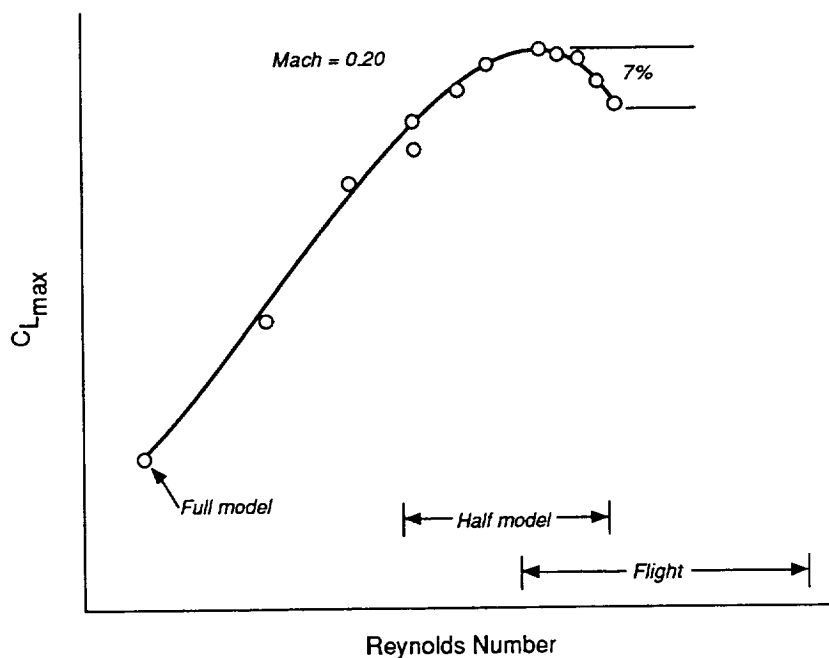
The efficiency and effectiveness of the low-speed, high-lift systems employed by subsonic jet transports for takeoff and landing have a major impact on overall economic performance. The need is to develop design technology that will produce high-lift systems that provide high L/D in climb-out, high lift coefficient during landing approach, acceptable performance in icing conditions, and acceptable levels of airframe noise, and that are also amendable to low-cost manufacture and maintenance.

The payoff from continued improvements in high-lift systems is large. For an airplane the size of the forthcoming Boeing 777, a small increase in lift coefficient, 0.10, at a fixed angle of attack of 8.0 degrees, allows a 14.0-inch reduction in landing gear length and a 1,400-pound reduction in empty weight. A 0.035 (approximately 1 percent) improvement in maximum lift coefficient equates to a 1-knot change in approach speed, a 6,600-pound increase in payload (at constant approach speed), or a 60-foot reduction in landing distance. Simplifying the geometry of the flap system while maintaining aerodynamic performance yields large benefits in terms of cost and maintainability. One of the stated goals for subsonic transport design is the reduction of acquisition and maintenance costs by 25 percent relative to current production airplanes. Future advances in high-lift system technology can contribute significantly to the achievement of this goal.

Because of the complex physics and complex geometries associated with low-speed flight, CFD has not had a major impact on the technology of high-lift system design. The primary design tool has remained the wind tunnel, with some design guidance from CFD. Work over the past decade has verified the strong influence of Reynolds number on aerodynamic performance of high-lift systems—aerodynamic performance of high-lift systems in many cases does not scale predictably with Reynolds number. Figure 7-1 shows the experimentally measured maximum lift coefficient of a simple swept wing over a range of Reynolds numbers, which displays large and unpredictable variations in maximum lift with Reynolds number. Such experiments demonstrate that the best aerodynamic performance and lowest risk can be achieved only by carrying out the aerodynamic design and validation at flight Reynolds numbers. Because of this, airframe companies do their development work in high Reynolds number wind tunnels—which, for the design of the new Boeing 777, meant extensive development work in European wind tunnels.

The following developments in the technology for advanced high-lift system designs are needed:

1. Improved understanding and measurement of the detailed flow physics at wind tunnel and flight Reynolds numbers: A better understanding is needed of turbulence and its modeling; of boundary layer transition, laminar bubbles, turbulent reattachment and relaminarization phenomena; and of merging boundary layers and wakes, including the detailed behavior of the viscous layers and wakes in the high adverse pressure gradient region above the trailing edge flaps. Some progress is being made in the United States in this area of research. In contrast, the Europeans have greatly exceeded U.S. technology in high-lift systems,



Source: Boeing Commercial Airplane Group

FIGURE 7-1 Variation of  $C_{L_{max}}$  with Reynolds number for a simple swept wing.

principally through their concerted efforts over several years to understand the detailed flow physics associated with high lift. For the United States to compete in this area, greater investment is needed in the experimental capabilities and flow physics studies that lead to breakthroughs in high-lift capabilities.

2. **Improved CFD:** The challenge is formidable in view of the complex physics, complex geometries, and numerous length scales that must be resolved numerically. Pacing items are the flow models (modeling of turbulence, transition, bubbles and reattachment, merging shear layers, and relaminarization); the sheer size of the computational problem, including proper numerical resolution of all the important length scales of the physics; and code validation, particularly at flight Reynolds numbers where few data exists. What is needed is a CFD development program that is closely coordinated with other key elements of flow physics and high Reynolds numbers testing, and which is constrained to be economically viable and runnable in a timely manner when hosted on today's computers. Although the United States leads in certain respects in CFD, at current investment levels, U.S. research efforts will not provide for the experimental validation of CFD capabilities necessary to maintain this lead. The need for such validation has been recognized for some time as critical to the maturation of such computational capabilities for ultimate use in design method applications.

3. Experimental research and developmental testing at the highest achievable Reynolds numbers: There is a major need for a low-speed, low-disturbance testing facility in the United States, one that produces the highest reasonable Reynolds numbers at the right Mach numbers and closely simulates the freestream environment of flight with levels of productivity that are needed to support developmental testing. It is no longer acceptable to develop a candidate design at low Reynolds numbers and validate it at high Reynolds numbers. There is also a strong need for obtaining aerodynamics measurements at flight Reynolds numbers on full-scale flight vehicles. Nonintrusive, highly accurate, and responsive instrumentation is urgently needed to make detailed measurements of various flow conditions on and away from the surfaces of a test article. The current level of U.S. high-lift research efforts will not provide the advanced measurement technologies needed for rapid, competitive progress in this research area. In 1989, NASA developed a broad plan for research in advanced aeronautics measurement technology; unfortunately, the plan was never implemented. In comparison, the European competitors, in their BRITE EURAM program, have committed to significant levels of investment in measurement technology.

Other phenomena associated with high-lift systems are airframe noise and wake vortex prediction and alleviation. Continuing advances in engine noise reduction will mean that the airframe is responsible for a growing portion of the overall noise profile of an airplane. Reducing airframe noise requires an understanding of the detailed sources and mechanisms of its production. The design challenge is to develop solutions that reduce airframe noise but retain high-lift aerodynamic performance.

Airplanes that meet the Federal Aviation Regulation (FAR-36) Stage 3 noise limits have provided substantial noise reductions relative to older airplanes. Nevertheless, many airports impose additional noise restrictions that penalize payload or range by requiring operations at reduced takeoff weight or that prohibit night operations. It is clear that pressure to further reduce noise will continue to increase.

To advance the state of the art to significantly reduce noise, concerted and continuing research and development efforts are required. NASA should lead the basic research to substantially improve the sophistication and technical strength of noise analysis/design computational tools. The agency should also lead the development of novel noise reduction concepts. The Committee recommends that NASA:

- conduct and sponsor fundamental research to understand and reduce high-speed jet and turbomachinery noise;
- conduct and sponsor fundamental research to understand human response to noise and vibration in aircraft cabins, flight decks, and crew rest areas;
- develop the technology for predicting and measuring long-range ground-to-ground and in flight-to-ground sound propagation for airport and en route noise assessment;
- develop technology for the prediction and control of vibroacoustic responses of aircraft structures and materials;
- develop prediction and suppression technology for near- and far-field noise;

- develop experimental techniques and facilities to permit acquisition of accurate acoustic, aerodynamic/structural dynamic, and psychoacoustic data in support of aircraft acoustic technology development; and
- develop signal processing technology to improve analysis and utilization of data from acoustic wind tunnel testing.

Unless the United States mounts concerted efforts to augment the development of advanced computational and experimental capabilities, it will not be possible to achieve technology parity with similar European efforts. In particular, U.S. acoustic research facilities are not as capable as those in Europe (particularly DNW in The Netherlands). In the absence of these acoustic research facility capabilities in the United States, our industry and government research and development efforts typically utilize foreign facilities. In order to compete, it is necessary for the United States to support the development of appropriate facilities.

Many airports around the world are reaching capacity operations, limited in part by wake vortex separation requirements on landing and takeoff. Continued growth of the air transport system will require increases in airport capacities. Finding ways to reduce airplane separation requirements would contribute to that goal. Studies of wake vortices, prediction methods, means of vortex detection and avoidance, and means for promoting rapid dissipation of wake vortices should be continued and expanded. Wake vortex research program plans have been developed jointly by NASA and the Federal Aviation Administration (FAA). Unfortunately, work has not begun on carrying out this plan.

NASA should play a leading role in the development of the enabling technologies in these areas. There should be a combined program of flow physics and CFD, which together will increase understanding of the complex flow physics and impart an ability to predict and compute such flows. Comprehensive programs that address the issues and opportunities in noise research, wake vortices, and airplane separation requirements are needed. NASA is the appropriate organization to develop the technology and means for testing at the highest Reynolds numbers, which includes advanced flow diagnostic instrumentation development, innovative wind tunnel circuit components, the possible use of heavy gas, moderate cryogenics, and other options for high Reynolds numbers, half-model testing techniques, and wind tunnel wall interference minimization.

The resources required in particular for the development of a very high Reynolds number wind tunnel are large, but investment for that purpose is essential if the U.S. competitive edge is not to be further eroded.

Investments by NASA in the technology areas described above will benefit all segments of the industry, not just large commercial transports. Commuter and short-haul aircraft will benefit from advances in the enabling technologies of flow physics, CFD, and experimental research.

## **SUBSONIC AIRCRAFT PROPULSION/AIRFRAME INTEGRATION**

The technology of integrating propulsion systems and airframes involves the ability to assess and control the development of wave drag, induced drag, and profile drag. Advances in CFD over the past decade have contributed greatly to this technology. It is anticipated that ongoing CFD developments will lead to even further refinements.

Two areas remain in which technology improvements are needed. One is the development of wind tunnel test techniques and powered propulsion simulators to better represent installed power effects of the forthcoming generations of very high bypass ratio engines in wind tunnel testing. The other is the need to predict the installed characteristics of thrust reversers, both computationally and with wind tunnel testing techniques. These are areas in which NASA can make important contributions.

## **AERODYNAMIC CRUISE PERFORMANCE**

Although the fundamental physical principles of subsonic and supersonic airflow around aircraft are the same, design approaches to minimizing drag are greatly affected by the cruise speed. This section of the report discusses cruise performance in the two speed ranges separately.

### **Subsonic Aircraft Cruise Performance**

Long-haul subsonic transports are now, and will be for the foreseeable future, the major product of the civilian aviation industry and infrastructure. As noted in Chapter 2, from 1975 to 1995, aerodynamic efficiency will have increased by approximately 10 percent, and if the current rate of improvement is maintained, another 5–10 percent is projected by the year 2020. However, ordinary development or evolution alone will not keep the United States at the forefront in the world market. Although continued evolutionary advances in methods and processes (experimental, theoretical, and computational) are needed to provide continued improvement of aerodynamic design technologies, demonstrated innovative technologies are necessary in the longer term to provide opportunities for significant improvements in performance.

### **Laminar Flow Control**

The flow on most of the surfaces of an aircraft is turbulent. Laminar flow control (LFC), hybrid laminar flow control, and natural laminar flow are promising sources of skin-friction drag reduction on aerodynamic surfaces. Laminar flow nacelles are also being studied by NASA. Laminar/turbulent transition of the airflow next to the aircraft surface is delayed through a combination of pressure gradient tailoring of the wing and control such as suction through the skin. If full-chord laminar flow can be maintained in this fashion, fuel savings of up to 25 percent could be realized.

Transition is extremely sensitive to freestream conditions (e.g., freestream turbulence and acoustics) and surface roughness (e.g., rain and ice crystals, insect debris, surface finish, and fasteners); lack of confidence in these issues has hindered the use of this concept on vehicles. Also, of perhaps greater significance have been the questions of fabrication cost and operational cost and maintainability.

Engineering and optimization tools have outpaced the state of the art in transition prediction theory.<sup>1</sup> Thus, the design of LFC, hybrid laminar flow control, and natural laminar flow systems depends on empirical bases to determine transition. This method is also limited because it cannot account for the effects of surface roughness and freestream disturbances.

Knowledge of transition—so very important to the success of LFC techniques—is, in general, limited to the simplest of geometries. Efforts to better understand the transition flow physics are under way to provide valuable guidance for the surface roughness and freestream disturbance problems.

Only a limited number of flight tests have been flown since the original and successful X-21 program of the 1960s;<sup>2</sup> these are the JetStar (NASA/Langley) and Boeing 757 (NASA/Boeing). In both cases, extensive laminar flow was successfully achieved on the upper surface of the swept wing through the use of suction. Very low suction levels were required, with power penalties of the order of 1 percent. Studies with engine noise indicated no effect. The use of a Krueger nose flap eliminated a potential buildup of insect debris on the leading edge.

The remaining challenges to the implementation of laminar flow technology in large subsonic transport designs include validation of the technology in actual airline service operating environments and exploration of the technical issues associated with making laminar flow operate effectively on the inboard portion of the wings of very large aircraft. Recognizing the challenges, during 1990 NASA and the industry developed a cooperative research plan; however, these efforts have been delayed by overall program constraints. Meanwhile, the Europeans have rapidly advanced their laminar flow efforts. Airbus plans for laminar flow technology validation include extensive large-scale testing, targeting technology validation as early as 1993.

### **Turbulent Drag Reduction**

The most promising technique demonstrated thus far has been passive control by riblets, tiny streamwise grooves on the aircraft surface. This device is useful for surfaces on which laminar flow is very difficult to achieve (e.g., the fuselage). The approach was used

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<sup>1</sup> Bushnell, D.M., M.R. Malik, and W.D. Harvey. 1989. Transition Prediction in External Flows via Linear Stability Theory. Symposium Transonicum III, J. Zierap and H. Oertel, eds. Berlin, Heidelberg: Springer Verlag.

<sup>2</sup> Bushnell, D.M., and M.G. Tuttle. 1979. Survey and Bibliography on Attainment of Laminar Flow Control in Air Using Pressure Gradient and Suction.

successfully on the U.S. entry in an America's Cup Race and then flight-tested on a portion of a business jet,<sup>3</sup> achieving a reduction in local skin-friction drag of 8 percent.

The state of the art in turbulence predictions depends on empirical correlations and models, usually developed for one set of flow conditions or a very simplified model. Here also, efforts at understanding the basic physics of turbulent flow are under way. Prediction and control have been hindered by the lack of reliable, efficient models of turbulence for complex geometries.

### **Advanced Supercritical Airfoils**

Advanced supercritical airfoils, which reduce the shock strength on transonic airfoils, have contributed to drag reduction and have been used on all commercial transport aircraft developed since 1975. Further modifications<sup>4</sup> with reduced moments and weaker shock waves are under study by NASA for use with LFC systems.

Improved understanding of shock/boundary-layer interactions has led to new opportunities to greatly improve airfoil design concepts and procedures.

### **Wing Design**

The improvement of theoretical analysis tools and CFD, coupled with a better understanding of flow physics, has enabled the design of more aerodynamically efficient wings with greater thickness and reduced sweep. This allows a wing weight reduction or higher aspect ratio. Substantial improvements in cruise Mach number and critical Mach number have also been realized. New opportunities exist to significantly improve the design optimization procedures for wings that incorporate laminar flow systems along with advanced high-lift systems.

### **Winglets**

Winglets, or wingtip extensions, which first appeared on business jets, are now used on various versions of commercial transports (e.g., the Boeing 747-400 and MD-11). These effectively increase the aspect ratio of the wing. Advancements in understanding of the "nonlinear" effects of wing-wake deflection and roll-up have created opportunities to improve the design optimization procedures for winglets and other wingtip devices for drag reduction. In each of these technology topics, significant opportunities have developed to advance the state of the art; however, constraints on the aeronautics program have limited NASA's ability to

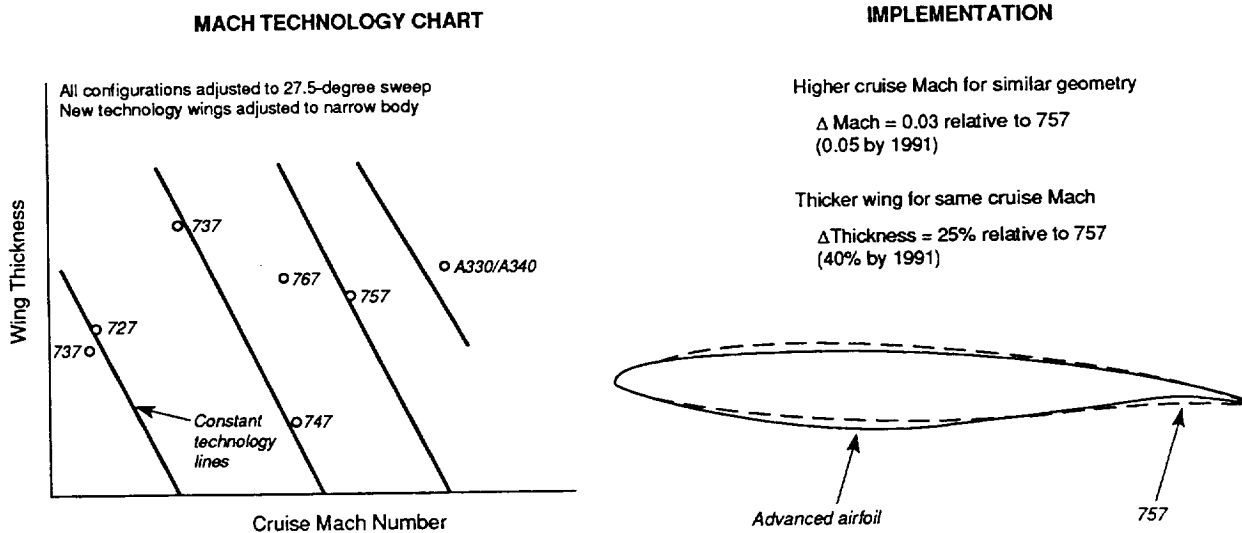
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<sup>3</sup> Walsh, M.J., W.I. Sellers, III, and C.B. McGinley. 1988. Riblet Drag Reduction at Flight Conditions. AIAA Paper No. 88-2554. Washington, D.C.: American Institute of Aeronautics and Astronautics.

<sup>4</sup> Pfenninger, W., and C.S. Vermu. 1988. Design Aspects of Long Range Supersonic LFC Airplanes with Highly Swept Wings. SAE Technical Paper 88-1937. Washington, D.C.: Society of Automotive Engineers.



support the needed advancements in experimental or computational capabilities and in ground and flight validation of these technologies.



Source: Boeing Commercial Airplane Group

FIGURE 7-2 Improvements in transonic wing technology.

### Status of Subsonic Technology

As noted earlier, the past decade has seen large improvements in wing design technology, the successful demonstration of laminar flow control on a Boeing 757, the successful demonstration of riblets on a business jet, the successful demonstration of natural laminar flow on a business jet, and the use of supercritical airfoils and winglets on transports in everyday commercial service.

Advances in computer and quiet-tunnel/instrumentation capabilities have allowed details of the fundamental flow physics of transition and turbulence to be studied. Computational time for these efforts, however, is too long for extensive use in the design process at present.

NASA should play a leading, but not exclusive, role in the development of enabling technologies. There should be a cooperative effort among NASA, industry, and academia to research complicated flow physics with the goal of predicting, modeling, and controlling such flows. Research should combine theory, careful experiments, and CFD; duplication of the

results by another technique or in another facility, as recommended by the U.S. Transition Study Group, is also desirable. NASA is an appropriate organization to encourage flight testing of enabling technologies and the development of advanced diagnostic instrumentation for nonintrusive testing. NASA is also an appropriate organization to provide high Reynolds number, quiet testing opportunities, as well as the most current computational facilities and techniques.

To implement the above concepts, a better understanding of flow physics is required. Intensified efforts to develop useful, accurate engineering models that can be used for design are particularly necessary. This work, although seemingly basic in nature, must be actively pursued and must include companion theoretical, computational, and experimental efforts conducted under careful, well-documented conditions. A better understanding of flow physics will also afford the opportunity for effective use of flow control. Issues to be addressed should include implementation, reliability, and maintenance of the mechanical systems, as well as implications of the loss of the system in flight. Continuing advances in CFD, as well as high Reynolds number, low-disturbance experimental capabilities, are also needed in support of the evaluation and design of these concepts.

NASA needs the following resources to accomplish the foregoing:

- high Reynolds number facilities (simulate flight),
- low-disturbance freestream facilities (simulate flight),
- full-scale Reynolds number flight research capability,
- nonintrusive instrumentation,
- faster and bigger computers for flow physics (model development),
- more efficient CFD, faster algorithms and grid setups,
- companion theory/computation/experiment efforts (validation and guidance), and
- NASA/industry/university cooperation on approximately equal levels. NASA's role in the university training of future engineers through research funding must never be overlooked.

The Europeans are using much of the technology described above—particularly LFC—even though by U.S. standards the technology is often untested or unproven. On an overall technical basis, current European offerings are equal to those of the United States. However, because Europeans are incorporating the technology faster than the United States is, their rate of improvement is significantly greater. In particular, within the BRITE EURAM consortium involving government, industry, and academia in Europe, a highly organized effort has been developed to advance the state of the art for laminar flow engineering design capabilities. Their efforts combine the best talent and facilities in all of Europe to develop and validate transition prediction tools for integration with industry engineering design methods. (BRITE EURAM efforts address all other aeronautical disciplines as well.) Although progress is being made in the United States on understanding boundary-layer transition physics, no similar design-tool-focused effort is being funded here. The problem in this country is not lack of opportunities, but rather the lack of priorities on resources.

### **Supersonic Aircraft Cruise Performance**

U.S. expertise in supersonic aircraft performance stems from the earlier Supersonic Transport (SST) program, the ongoing Phase I High Speed Research Program, and various high-speed fighters. In cruise, the recognized promising technologies for the HSCT are the same as for the subsonic case: hybrid laminar flow control by suction and pressure gradient. Unlike the subsonic speed regime, this technology has not been demonstrated in flight. The benefits of lower drag (as described in subsonics) and thermal requirements associated with laminar flow can be realized in this flight range as well. In addition, technology advances in the fundamental understanding of high Reynolds number effects on leading-edge vortex formation and the ability to eliminate unacceptable characteristics, such as low speed pitch-up, could allow the utilization of highly swept, high-performance wing planforms. This would provide substantial increases in cruise lift-to-drag ratios over the currently favored planform concepts.

### **Laminar Flow Control**

At present, our knowledge of high-speed transition is even less developed than our knowledge of subsonic flows; designs depend on existing theories that are not compatible with design and optimization tools (as described in subsonics). In the supersonic range, however, the effects of freestream conditions (e.g., freestream turbulence and noise) and surface roughness may be more severe than in subsonic flows. Efforts are under way to understand and predict the transition behavior in supersonic flight. The exciting progress that has been made in subsonic laminar flow technology required nearly four decades of concentrated, if not continuous, effort. Although some of the subsonic lessons learned may apply to supersonic laminar flow challenges, it would be overly optimistic to expect supersonic laminar flow technology to mature after a few years of effort. The United States should prepare for a long-term commitment to supersonic laminar technology development in order to lead in this area. Currently, U.S. research and development resources in this area, while not inconsequential, will not support a long-term effort to achieve technology maturation and validation.

The single low-disturbance, supersonic, experimental facility available for this basic work in the United States is the Mach 3.5 Quiet Tunnel at NASA/Langley,<sup>5</sup> which is just beginning to contribute invaluable information. Large-scale, low-disturbance, supersonic wind tunnels are needed to support aircraft development. The existing infrastructure of government facilities and capabilities that support the U.S. subsonic airframe industry was built up over many years. If this nation is to compete successfully in a future class of supersonic aircraft, investment in the facility infrastructure must begin soon. These investment requirements are relatively large because of the unique facility needs and the needs for flight capabilities.

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<sup>5</sup> Beckwith, I., F. Chen, S. Wilkinson, M. Malik, and D. Tuttle. 1990. Design and Operational Features of Low-Disturbance Wind Tunnels at NASA Langley for Mach Numbers 3.5 to 18. AIAA Paper No. 90-1291. Washington, D.C.: American Institute of Aeronautics and Astronautics.

### **Turbulence Models**

The art of turbulence modeling is very young and depends on very limited experimental data (often at low temperature). Here also, efforts at understanding the basic physics of turbulent flow are under way. CFD is being used for flow physics studies.

### **Sonic Boom**

It is very unlikely that the HSCT would ever be allowed to fly supersonically over land if the problem of sonic boom is not resolved. Efforts are under way to tailor the shape of the airplane so as to modify the sonic boom to acceptable levels, although with some degradation of performance. The economics and performance of a combination of operational modes for missions over land and over water, including subsonic/supersonic, low/high supersonic modes, and different single supersonic cruise Mach numbers, are being analyzed.

### **Subsonic Cruise**

If a vehicle must also fly subsonically over land, the configuration designed to best utilize supersonic LFC may not perform well at lower speeds. Here, again, trade-offs are needed between supersonic and subsonic flight design to optimize overall economy and performance.

### **Status of Supersonic Technology**

A major step in the last decade has been the successful correlation of transition prediction theory with experimental results in the NASA/Langley Mach 3.5 Quiet Tunnel. This has established the standard for future supersonic and hypersonic facilities as well. It is strongly recommended that all future facilities have the same features for noise control as the Mach 3.5 Quiet Tunnel.

To demonstrate LFC design methodologies and develop 50–60 percent chord laminar flow, plans are under way for an F-16 XL flight test at Mach 2. These efforts to validate existing ground facilities and methodologies with actual flight are important. Plans are under way at NASA/Langley for the development and fabrication of a series of low-disturbance facilities at various Mach numbers.

The biggest challenge is to achieve good overall cruise economics with acceptable community noise and emissions levels.

The challenges for L/D enhancement include LFC, turbulent drag reduction, reduction of drag due to lift, volume wave drag reduction, and the development of design optimization methods. The following ideas appear promising, but studies in the past have proved inconclusive:

- improvement of conventional shapes;
- flying yawed wing (Mach number 1.6);<sup>6</sup>
- extreme arrow wing, strut bracing, multiple bodies, extensive LFC;<sup>7</sup> and
- enhanced favorable wave interaction (e.g., optimized parasol wing, multiple bodies).

More speculative approaches for supersonic drag reduction include:

- increased lift from upper surface via flow separation control (reduced sonic boom?); increased leading-edge thrust; increased fuselage lift/camber and reduced wave drag due to lift; control of shock/boundary-layer interactions (e.g., by passive porous walls); improved isentropic compression surfaces/inlets;
- multistage aircraft (e.g., separate subsonic takeoff and landing carrier);
- thrust vectoring for lift augmentation;
- mission-adaptive wings (subsonic/supersonic);
- application of conventional takeoff and landing aircraft vortex drag due to lift reduction approaches (other than aspect ratio); and
- engine exhaust flow tailoring for partial shock reflection/favorable interference wave drag reduction.

To implement the above concepts, a better understanding of flow physics is required. Only in this way can useful, accurate engineering models be developed for design. This work, although seemingly basic in nature, must be actively pursued and must include companion theoretical, computational, and experimental efforts conducted under careful, well-documented conditions.

Continuing advances in CFD, as well as large-scale, low-disturbance experimental capabilities, are also needed in support of the evaluation and design of these concepts.

## LOW SPEED AND HIGH LIFT FOR SUPERSONIC CONFIGURATIONS

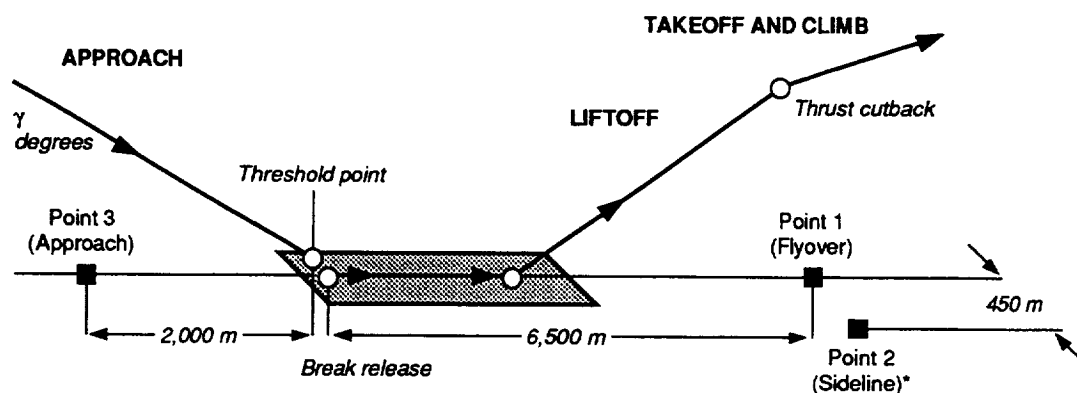
High-speed configurations present a particular challenge for takeoff and landing performance as a result of the usually high wing sweep and slender designs required for supersonic performance. Supersonic aircraft must be designed to operate from existing international airport surfaces; therefore, operation for an 11,000-foot runway at maximum takeoff weight is a requirement. High-lift capability significantly affects the approach speed, field length, and time to climb—which in turn, affect the noise footprint. FAR 36 measurement locations are illustrated in Figure 7-3. Aerodynamic L/D improvements for takeoff reduce community noise levels by reducing climb-out time or permitting reduced thrust levels. Landing

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<sup>6</sup> Jones, R.T. 1986. Flying Wing SST for the Pacific. *Aerospace America* 24 (November): 32-33.

<sup>7</sup> Pfenninger and Vermu, op. cit.

requirements include high-lift generation at high drag while maintaining pilot visibility for approach. In addition, slender configurations usually require stability and control features to delay the pitch-up tendencies and to increase lateral control effectiveness. In addition, high-lift devices must work in harmony with other advanced concepts such as supersonic laminar flow control that are beneficial to supersonic cruise efficiency. These requirements result in ample opportunity for innovative and aggressive aerodynamic development.

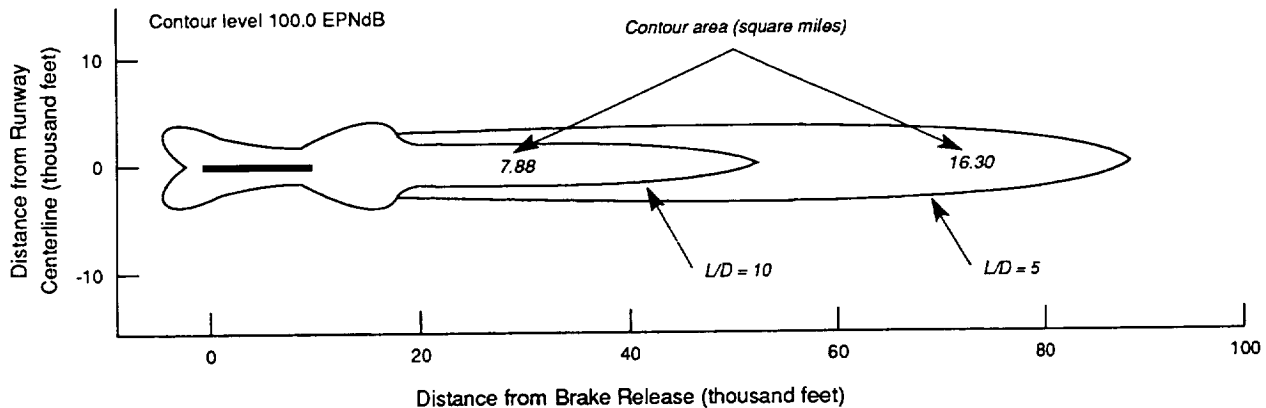


Source: National Aeronautics and Space Administration

FIGURE 7-3 FAR 36 measurement locations.

First-generation supersonic transports, such as the Concorde and Tupolev 144, do not meet current environmental requirements at most locations. The Concorde relies on vortex lift at a large angle of attack to achieve its lift for takeoff and landing. The result is a very high-drag situation with strong trailing vortices and landing visibility that must be augmented by a hinged nose section. There is significant room for improvement in developing low-speed, high-lift operation and control. Since the configurations are slender, much of the flow is separated at high-lift conditions. There has been significant progress over the last decade in finding new ways to avoid separation, as well as to take advantage of separated flows by controlling the vortices and positioning them to achieve maximum benefits. Vortex flaps have been used to significantly improve the lift-to-drag ratio and maintain a larger extent of attached flow. A lower noise footprint may be achieved for climb-out by improving the climb-out angle. The effect of lift-to-drag ratio on climb-out noise footprint is illustrated in Figure 7-4. Because of the very large levels of noise suppression required, HSCT noise suppression devices installed on engine or airframe are quite heavy. Increasing high-lift system performance also entails significant weight increases. NASA should intensify its efforts to develop more efficient HSCT high-lift system devices having minimum weight increments; such devices could provide very significant economic benefits to an HSCT vehicle.

Technology challenges for the future revolve around ways to find the low-noise, high-L/D solution to the takeoff problem. Vortex control becomes an important way to achieve these results by enhancing leading-edge suction and maximizing the attached flow in the wing



Source: National Aeronautics and Space Administration

FIGURE 7-4 Takeoff noise contours.

at high angles of attack, thus improving the effectiveness of the wing.

CFD can provide a useful tool in dealing with the separated and vortical flows. However, since Reynolds number dependency may be significant, complete validation of CFD must be accomplished before design application can be made. The Reynolds number uncertainties lead to a need for high Reynolds number facilities that can provide large-scale testing of the supersonic configurations at low speeds. Blending of propulsion systems by vectoring or directing bleed air may be useful in finding an optimal solution to the overall control and lift drag balance for the aircraft. Because supersonic laminar flow control may play an important part in the supersonic cruise efficiency of high-speed vehicles, careful attention must be paid to the interrelationships of the high-lift system and the suction system used for laminar flow control.

## SUPERSONIC AIRCRAFT PROPULSION/AIRFRAME INTEGRATION

With increasing cruise flight speeds, the achievement of close aerodynamic coupling between the propulsion system and the airframe becomes more and more important. One seeks favorable aerodynamic interference between the two systems so as to minimize overall drag and optimize engine performance. NASA has conducted extensive interference tests involving variations in Mach number, angle of attack, nacelle position, and nacelle mass flow on configurations from isolated nacelles to wing-body-nacelles up to Mach number 1.4. These tests showed considerable interference drag near sonic speed and also showed that interference effects were dependent on angle-of-attack and mass flow variations. NASA is presently extending these tests to a Mach number of 2.5.

The development of an HSCT will require a large effort in integrating engine and airframe and in minimizing engine noise. This area is also receiving much attention in Europe for large commuters as well as a second-generation supersonic transport. European expenditures on propulsion/airframe integration are rapidly growing.

### **Inlets**

Inlets of air-breathing engines for supersonic aircraft up to Mach 3.5 can presently be designed to provide high pressure recovery and minimum inlet flow distortion and drag.<sup>8</sup> This capability demands close coupling of the inlet with the forebody of the fuselage or the wing. The latter is designed to provide effective initial compression and reasonable uniformity of the incoming air flow. To achieve this condition, the design includes a bleed to prevent the retarded flow of the fuselage forebody or wing boundary layer from being ingested in the inlet. Engines for supersonic aircraft should also be designed with variable geometry inlets to reduce sensitivity to flight conditions and, in particular, to enable efficient operation at takeoff and landing, as well as in cruise flight. Such inlets will require sophisticated boundary-layer control systems. It is expected that such variable geometry inlets can be developed to operate efficiently from subsonic speeds up to Mach 6.

### **Nozzles**

The data base for axisymmetric nozzles is substantial, and the data base for nonaxisymmetric nozzles of the two-dimensional type of moderate aspect ratios is increasing. In the design of high-performance nozzles, emphasis has been placed on achieving a reduction in transonic drag and a reduction in the complexity of the system.

Future efforts need to focus on development of multifunctional nozzles with reduced drag levels over a wide range of Mach numbers, providing significant increases in cruise performance at supersonic speeds. These efforts will be greatly enhanced by the availability of powerful new numerical techniques.

Consideration also needs to be given to the potential of vectored thrust for both cruise and maneuvering operations.

### **Noise**

For supersonic aircraft, reducing engine noise generated by the very high jet velocities requires major efforts. The Concorde, which represents the current state of the art for SSTs, generates noise that is approximately 20 EPNdB<sup>9</sup> higher than Stage 3 subsonic airplanes of the

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<sup>8</sup> National Research Council. 1985. *Aeronautical Technology 2000: A Projection of Advanced Vehicle Concepts*. Washington, D.C.: National Academy Press.

<sup>9</sup> Effective perceived noise in decibels.



same takeoff weight. To be fully acceptable for commercial use, future supersonic transports will have to be designed to the same noise limits as subsonic airplanes. These results present an extraordinary challenge currently being addressed by industry and NASA. Such schemes as ejector-suppressor nozzles will help reduce the main contributors to jet noise, which are turbulent mixing and shock cell noise.<sup>10</sup> Very little is known about airframe noise of the delta wing planform of supersonic airplanes.

## **AERODYNAMIC ASPECTS OF CONVENTIONAL TAKEOFF AND LANDING FLIGHT DYNAMICS**

Advances in the prediction of flight dynamics characteristics of conventional takeoff and landing aircraft have not kept up with advances in other fields of aerodynamics. The following two sections discuss problems that must be addressed for subsonic and supersonic conventional takeoff and landing aircraft.

### **Subsonic Aircraft**

Stability and control testing is addressed early in flight test of a new aircraft configuration and is usually a large and expensive part of the development process. However, extraction of the aerodynamic coefficients from flight test data is still largely a trial-and-error process requiring many iterations. Parameter identification techniques have been attempted but have not been universally accepted as a standard method for flight data analysis by the commercial transport industry. Prediction of aerodynamic damping for conventional subsonic aircraft, for example, has not progressed much beyond the work done by the National Advisory Committee on Aeronautics in the 1950s. Also, the possible role of dynamic wind tunnel testing for commercial transports has not been explored.

Ground effects are also not well predicted. A major portion of simulator crew training is in ground effects, and many man-hours are required to achieve an adequate match with flight test data. Autoland certification is also a problem because systems based on wind tunnel data and predicted aerodynamic characteristics often require corrections derived from expensive flight testing. Furthermore, little work has been done in recent years to correlate dynamic characteristics with pilots' opinions. Failures of stability augmentation systems and the presence of sophisticated flight control system modes must be studied for their effects on minimum safe handling qualities.

The use of laminar flow control techniques may also lead to further departures from familiar characteristics, as well as generating the need for a priori modeling of the feedback loops required to modulate the laminar flow.

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<sup>10</sup> Boeing Commercial Airplane Group. 1990. High Speed Civil Transport Program Review (brochure). Seattle, Wash.

In general, then, all of the aerodynamic coefficients are obtained through theoretical means, with empirical adjustments. Flight regimes in which the aerodynamics are nonlinear, at transonic speeds or at high angles of attack, for instance, have been especially troublesome. Greater application of computational aerodynamics could provide more accurate predictions and better consistency but, at present, there is no sound body of data to correlate the empirically derived derivatives used in the early design process.

In the past the lack of complete knowledge of dynamic flight characteristics has been tolerable because the undesirable dynamic characteristics could usually be compensated with electronic feedback control systems. However, there remains the risk that significant problems requiring design modifications will be uncovered late in the testing process. This is particularly true for advanced aircraft configurations. The later the problems are found, the more difficult and expensive they are to fix. Thus, it is important that sufficiently accurate techniques be applied to predict dynamic characteristics from the beginning of the design effort.

A better technical base is clearly needed to address stability and control considerations with theoretically explicit analytical methods and with validated model testing techniques in the early stages of design. NASA is uniquely qualified to address this situation based on its extensive work on dynamic stability of military aircraft and other exotic configurations that represent radical departures from past practice.

NASA should undertake a systematic, in-depth review of current practice in the dynamics and control of aircraft, initiate a program to extend the applications of CFD methods to a priori analysis, and include an extension of model wind tunnel testing to dynamic derivatives. The final goal is to develop methods for systematic correlation of the predicted characteristics with flight test data.

### **Supersonic Aircraft**

The problem of predicting dynamic characteristics prior to the full scale test phase is particularly critical for the HSCT. The HSCT will have a very wide speed range, will require large angles of attack for takeoff and landing to develop the required lift, and will have strong aeroelastic interactions with highly nonlinear aerodynamic forces. It will be necessary for the designers to rethink the theoretical and experimental methods that are used to predict dynamic characteristics.

Although flight dynamics is not as critical an issue for the HSCT as its environmental compatibility, it is nonetheless prudent even at this early stage to begin incorporating flight dynamics into the iterative design process, and to begin refining the predictive capability for various flight regimes. It should be possible, for example, to first develop methods by using subsonic aircraft designs, since extensive flight correlation is possible, and then extend those methods to the special needs of the HSCT. It might be possible to take advantage of the SR-71 for a selective look at flight conditions unique to a supersonic transport once the subsonic flight dynamics technology is better established.

Because this whole area has received little attention in prior dialogue concerning opportunities for NASA research, it is recommended that NASA take appropriate steps to

specifically address the issue and establish where efforts can best be focused. Such a step should, among other things, review the degree to which flight dynamic technology now employed for subsonic and supersonic military aircraft can be applied to large transports.

## **AERODYNAMICS OF ROTORCRAFT**

For rotorcraft it is frequently difficult to separate the contribution of the conventionally defined disciplines. In particular, aerodynamics and dynamics are so closely coupled in the flexible rotor blades that most research and development on rotors must integrate both disciplines. The discussion that follows contains, therefore, considerable overlap—particularly with regard to vibration. In the sections that follow, the state of the art and recent progress on rotorcraft, including helicopters and tiltrotors, will be addressed jointly, followed by individual sections addressing the challenges and opportunities for conventional helicopters and convertible rotorcraft.

### **State of the Art and Recent Progress**

#### **Analytical Methods**

Semiempirical methods are generally adequate for conventional configurations with regard to performance and low-frequency flight dynamic phenomena; noise prediction codes are reasonably good where aerodynamic loads are known, but the inability to predict those loads is severely limiting for critical conditions such as approach and high-speed cruise. Flight dynamic codes, while serviceable for simulation of moderately stabilized systems, are inadequate to predict stability limits of high-gain feedback systems and to adequately forecast tolerable levels of relaxed stability in systems designed to take advantage of active control, especially for larger aircraft in which airframe structural coupling is significant. For less conventional configurations, such as bearingless rotor helicopters and tiltrotors, the ability to extrapolate existing codes is even more questionable.

#### **First-Principle CFD Codes**

First-principle CFD codes are not yet in general use by the helicopter industry, although some are beginning to be available for the study of discrete phenomena such as the flow around rotor tips at specific azimuth positions. Most industry hover performance codes continue to use empirically derived wake geometries (or geometries derived from model wind tunnel tests), which appear to be adequate for rotors that do not depart radically from prior experience. However, these codes tend to break down with large variations in twist disk loading or tip geometry. Another gap in predictive capabilities relates to the interaction of rotor and airframe.

This becomes particularly critical for tiltrotors. An extensive wind tunnel test on this problem as experienced by conventional helicopters has just been completed using a Bell 412 rotor in the 40' × 80' wind tunnel, and some experimental work has been done on the rotor wing

interference of tiltrotors, but analytical backup of this work to allow generalization to other design configurations is not yet available.

### **Test Methodologies and Facilities**

Techniques for the testing of model-scale rotors and helicopter airframes are well developed for performance and low-frequency stability phenomena. Wind tunnels adequate for 10-foot model rotors are generally available for the achievable envelope of modern helicopters, including tunnels with moving ground planes to enhance their low-speed-in-ground-effect fidelity, and the Ames facility extends this capability to full-scale helicopters up to the 10,000- to 20,000-pound class. The major gap is the lack of any U.S. tunnel for model-scale acoustic testing, for which only the DNW tunnel in Europe is truly adequate (and very expensive for U.S. industry). Flight test techniques that can truly separate the individual contributions of the rotor and airframes into performance, vibratory load, and flight dynamic phenomena, are also needed.

### **Design Concepts for Conventional Rotorcraft**

Concepts have been pretty well developed that allow the design of reasonably efficient helicopters with payloads up to 20 tons, operational ranges to about 400 miles, and cruise speeds from 150 to 180 knots. Somewhat larger helicopters could certainly be designed at some increase in program risk; the range could be extended if range is made a primary trade-off factor in the design; and higher dash speeds are achievable with a significant sacrifice in efficiency and payload (most easily by utilization of auxiliary propulsion and stub wings to provide some degree of high-speed maneuverability). The current speed record for a pure helicopter is 216 knots. Virtually all helicopters of any size use a significant degree of electronic stabilization (essential for instrument flight), and the most recent models have relaxed inherent longitudinal stability to take advantage of the potential for active control to provide larger center-of-gravity ranges and to reduce empennage requirements. Civil designs have been able to meet current FAA civil rotorcraft noise certification requirements, but these are still considered too noisy to encourage heliport use in all but relatively noise-insensitive areas.

### **Design Concepts for Convertible Rotorcraft**

After years of superficial exploration of a wide spectrum of configurations and in-depth exploration of the tiltwing in the XC-142 program and the tiltrotor through the V-22 program, a good basis now exists for defining the potential of each. The tiltrotor, because of its lower disk loading, appears to show the most promise for extending the speed and range of rotorcraft with the least compromise in the low-speed capabilities essential for confined area vertical takeoff and landing (VTOL) operations. Speeds to 300 knots have been demonstrated, and a reasonable payload fraction appears to be within reach.

## **Potential for Advancement and Major Challenges — Helicopters**

### **External Noise**

The major rotorcraft challenge for NASA is the reduction of external noise. The ability to predict whether a proposed new helicopter can meet noise certification requirements is critical. Both a priori codes and a methodology to extrapolate scale-model acoustic data to full scale are needed. The external noise problem remains particularly elusive, partly because the aerodynamic source of the noise varies radically from one flight condition to another. Again, much progress has been made on code development, and the time has come to put the emphasis on correlation and the acquisition of high-quality flight (or full-scale) data for correlation.

Secondly, criteria must be established to provide a noise level target that is reasonable to the communities in which heliport locations are proposed. Current criteria reflect more what can be achieved with current technology than what is required to gain community acceptance. These criteria should probably be defined in terms of noise footprint for terminal operations.

Because noise footprint is the critical factor in community heliport acceptance, control developments to allow steeper-gradient landings and takeoffs can play a major role in reducing the external noise problem. This is an excellent example of using advanced control technology to mitigate an aerodynamic problem.

Finally, and most important, technology to reduce rotor noise must be addressed. There are a number of approaches to quiet rotor tip noise that deserve evaluation. With a better understanding of tip vortex geometry to identify what factors may be manipulated to reduce the "blade slap" noise, more ideas should be forthcoming.

Rotor aerodynamic technology and transmission design technology that will allow reduction in rotor tip speed without unacceptable efficiency loss offer other attractive options.

### **Vibration**

External noise is followed closely on the priority list by vibration. Vibration problems have probably been the largest cause of major delays and overruns on derivative as well as new aircraft programs. Also, many of the mechanical failures that have occurred on rotorcraft have been traceable to the high vibration levels. Because cabin vibration results from a combination of the periodic aerodynamic loads and the structural dynamic response of the rotor and airframe, the vibration problem must be attacked on an interdisciplinary basis. The analytical tools required are thus a comprehensive rotor/airframe and aerodynamic/structural dynamic modeling effort. Considerable work in this area by NASA, the U.S. Army, and the helicopter industry has been under way for a number of years and is reaching maturity. What is needed now is a program to correlate these new integrated codes. The data base for such a correlation effort is about to be acquired on the UH-60, but a program to meticulously bring together the modeling codes and the data in order to verify the individual elements of these codes and their collective prediction capabilities must now be initiated.

Because a good part of the helicopter vibration and noise problem derives from the drastic variations in blade element angle of attack that occur as the blade rotates in forward flight, the potential benefits of introducing some variation in local blade angle of attack beyond that achievable with the conventional swash plate have been recognized for some time. The possibilities of individual blade control (operating on the rotating coordinates) and higher harmonic control introduced below the swash plate have been investigated, but the former demands excessive power and the latter, although of some benefit, is limited by the harmonics that can be introduced. What really has not been investigated is the possibility of introducing, at specific spanwise stations and azimuth positions, discrete, nonharmonic perturbations of the effective blade element angle of attack. Beyond mechanical blade element actuation, there are a number of novel ways in which this might be accomplished, for example, by the use of piezoelectric structures or by the application of pneumatic jet flap or circulation control technology. The extensive work on circulation control airfoils stimulated by the X-wing program provides a whole new foundation for investigation of such possibilities and should be explored.

### **Internal Noise**

Internal noise is also of very high priority for civil applications. For this problem, active noise suppression using canceling techniques seems to be a promising new approach and initial investigations of this possibility appear encouraging.

### **Aerodynamic Interaction**

As discussed above, developing the analytical tools to address the aerodynamic interaction of rotor and airframe requires attention to complement wind tunnel test programs recently undertaken. A special subset of this problem is the development of better concepts for rotor head drag reduction on conventional helicopters at high speeds and for rotor/empennage interaction improvement in low-speed flight.

## **Major Challenges/Innovative Approaches — Tiltrotors**

### **Wing Download**

With the first production tiltrotor prototype still under development, opportunities to improve tiltrotors are plentiful. At the top of the list is a means for reducing the wing download of the hovering tiltrotor. One obvious possibility is the use of flaps, but the opportunity for more radical solutions that might derive from a clearer understanding of the interactions should also be investigated.

### **Propulsion Efficiency**

Ranking in importance with the wing download problem is propulsion efficiency, which could be attacked by refined aerodynamics. NASA should apply the kind of thinking that went into the advanced turboprop design with a "clean piece of paper" approach to the problem of significantly improving and extending the propulsive efficiency/speed boundaries.

Geometries, operating revolutions per minute, aerodynamics, and structural dynamics deserve attention. A more radical proposal is to take advantage of variable-diameter rotor concepts that attack the basic problem facing the tiltrotor, namely, that a rotor sized for efficient hover is far too large for efficient high-speed flight.

Other aerodynamic and dynamic problems that also need to be explored are

- external noise reduction in the helicopter mode, particularly in approaches (this is probably amenable to the same aerodynamic research and development required for conventional helicopters);
- technology to allow steep-gradient and variable-speed approach envelope expansion to minimize noise footprint;
- active control for whirl flutter prevention with less wing weight penalty and—by allowing a more flexible, thinner wing—raising the Mach divergence limits and hence the cruise speed;
- active control for ride quality optimization, by recognizing that civil tiltrotors will spend more time at lower altitudes than will long-range jets (a flight dynamics/electronic control problem); and
- active control to allow smaller empennages, perhaps even canards, that will have less rotor/airframe interaction and lower weight (about one-half of the V-22 fuselage vibration is generated by rotor wake impingement on the tail surfaces).

### **Opportunities Common to Both Helicopters and Tiltrotors**

#### **Composites in Rotor Design**

One opportunity for NASA to help improve the maintenance cost situation for both helicopter and tiltrotors is the exploitation of composites, especially composites to make possible efficient, bearingless rotors. Although such rotors offer much promise by greatly reducing the number of individual parts and bearings, bearingless designs can introduce vibration, aeroelastic stability, and flight dynamic problems. Although these appear to be mostly structural dynamics problems, they are typical of the sort of problem in which aerodynamics and structures cannot be separated.

This technology for conventional helicopters has been the subject of research for some years, but tiltrotors present several new challenges. Evaluation of such rotor concepts makes excellent use of the considerable investment in the upgraded 40' × 80' full-scale tunnel. Such

work must be complemented by an adequate program on composites manufacturing and qualification technology.

### **Aerodynamic Test Facilities**

Finally, the top-priority facility requirement for both types of rotorcraft is to fill the gap identified above with regard to an acoustic wind tunnel capability. The need for such a facility has been recognized for at least five years and has also been strongly supported by the commercial fixed wing industry. Studies have been completed on several options. The most readily achievable solution appears to be the addition of acoustic treatment for the 40' × 80' full-scale wind tunnel. Funding for this facility has been the top-priority request for construction of facilities from the Ames Center, but it has not survived the cut at higher levels. Top-priority consideration of this facility upgrade is strongly recommended for the next construction-of-facilities funding cycle.

### **Resources Required for Rotorcraft**

Resources currently devoted to rotorcraft work are significantly below those applied to rotorcraft in the first half of the 1980s and need to be expanded to levels more comparable with this period. The discussion above defines the agenda in the aerodynamics area—and to a degree, because of the overlaps, in the structural dynamics and controls arena as well. To summarize, for helicopters, NASA should

- develop analytical tools for forecasting rotorcraft noise;
- in conjunction with the FAA, establish criteria for noise footprint allowable for neighborhood and city-center vertiports;
- develop control and human factor solutions to allow steep-gradient, variable-speed descents and takeoffs;
- explore opportunities for rotor noise reduction;
- correlate and validate analytical tools for vibration prediction and trade-off analysis;
- explore design techniques for rotor vibratory excitation suppression;
- explore techniques for internal noise suppression, including the use of noise-canceling means
- develop analytical techniques for assessing aerodynamic interference among rotorcraft rotors, airframes, and empennage.

For Tiltrotors NASA should

- develop and evaluate methods for reducing wing download in a hover;
- develop and evaluate concepts to improve tiltrotor propulsion efficiency;
- find ways to reduce external noise in the hovering mode;



- develop control and human factor solutions to allow steep-gradient, variable-speed descents and takeoffs; and
- explore the use of active control for (1) whirl flutter suppression, (2) ride quality optimization, and (3) empennage reduction (relaxed longitudinal stability).

For both helicopters and tiltrotors, NASA should

- explore the application of composites for rotor aerodynamic optimization;
- develop a high-quality acoustic testing capability for the full scale 40' × 80' wind tunnel at Ames; and
- revitalize industry/NASA program on all elements of rotorcraft noise. In the mid-1980s the "NR2" program run by NASA, the FAA, and the American Helicopter Society provided a very effective means of coordinating in-house and government-sponsored work on helicopter external noise. Although some of that activity is continuing, its level no longer brings together the critical mass of government and industry engineers that provided so much vitality to the program.

## **WIND TUNNEL, FLIGHT, AND AIR-BREATHING PROPULSION TEST FACILITIES**

The classes of aeronautical vehicles expected to meet commercial and military needs in the next 30 years fall in the range from low speeds to high supersonic speeds. These vehicles have been discussed in detail in previous chapters. The wind tunnels and air-breathing propulsion test facilities that will be needed to meet the design and testing requirements of these vehicles are discussed in the following sections. A discussion of flight testing and the use of CFD in vehicle design is also included.

### **Existing Facilities**

#### **Wind Tunnels**

Over the range from low to high supersonic speeds there are some 90 major wind tunnels in the United States and another 70 in foreign countries, including Canada, France, Germany, Japan, the Netherlands, and the United Kingdom.<sup>11,12</sup> Facilities with the greatest dimensions and Reynolds numbers are noted below; their ability to meet test requirements is discussed in later sections.

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<sup>11</sup> National Aeronautics and Space Administration. 1985. Aeronautical Facilities Catalogue. 1: Wind Tunnels (NASA RP-1132). Washington, D.C.

<sup>12</sup> U.S. Congress, General Accounting Office. 1990. Aerospace Technology—Technical Data and Information on Foreign Test Facilities (GAO/NSIAD-90-71FS). Washington, D.C.

The largest wind tunnels are

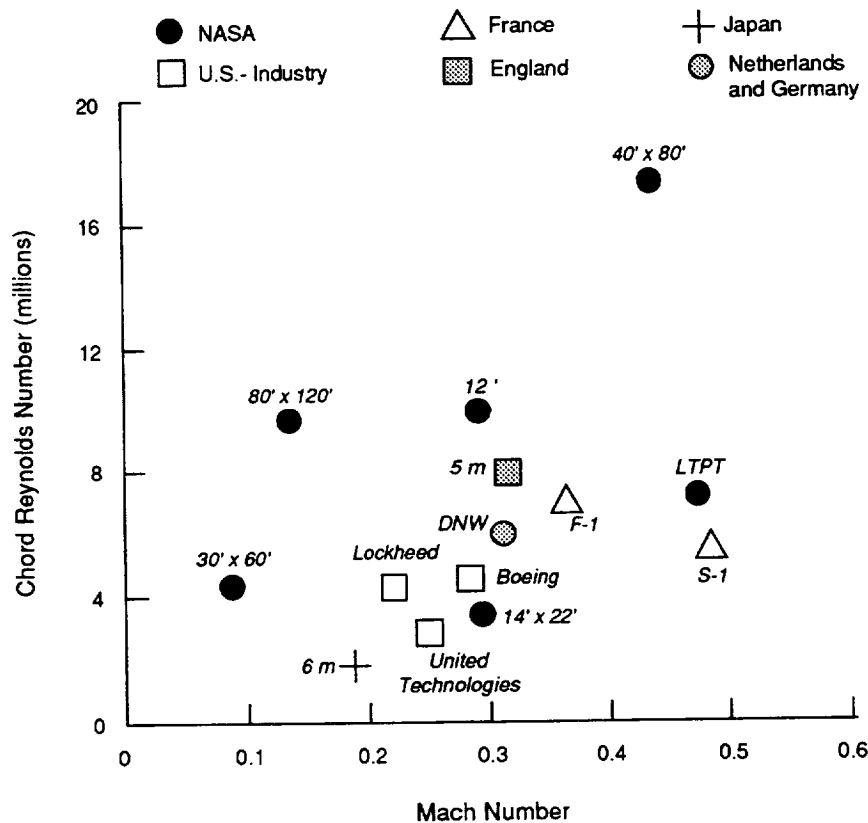
- subsonic: NASA Ames' 40'  $\times$  80' and 80'  $\times$  120'; NASA Langley's 30'  $\times$  60'; Canada's 30-foot; U.K. Royal Air Establishment 5 meter; Japan's 6 meter; and the Dutch/German DNW with three interchangeable test sections, of which the largest is 9.5 meters;
- transonic: NASA Ames' 14 foot and 11 foot; NASA Langley's 16 foot and its Transonic Dynamic Tunnel (also 16 foot); the U.S. Air Force's Arnold Engineering Development Center's 16T (16 foot); and France's S-1 (26 foot);
- supersonic: NASA Ames' 9'  $\times$  7' and 8'  $\times$  7'; NASA Lewis' 10'  $\times$  10' and 8'  $\times$  6'; U.S. Air Force Arnold Engineering Development Center's 16S (16 foot) and Aerodynamic and Propulsion Test Unit (16-foot dia.); Rockwell's 7 foot; and France's S-2 (6 foot).

Wind tunnels with the largest Reynolds number (given in parentheses in millions), based on effective chord length, are

- subsonic: NASA Langley's 7.5'  $\times$  3' Low Turbulence Pressure Tunnel (30); NASA Ames' 40'  $\times$  80' (17) and 80'  $\times$  120' (10); U.K. RAE's 5 meter (8); Germany's DLR cryogenic tunnel (8); and France's F-1 (7.5);
- transonic: NASA Langley's National Transonic Facility (120) and Transonic Dynamic Tunnel (TDT) (14); NASA Ames' 11-foot tunnel (10); and France's ONERA S-1 (10);
- supersonic: McDonnell Douglas' 4-foot Polysonic (200) and 4-foot Trisonic (120); Vought's 4-foot High Speed (150); Rockwell's 7 foot (130); Lockheed's 4-foot Trisonic (120); Canada's NAE 3-D (120); the Netherlands' 4-foot SST (120); and India's 4 foot (100). The McDonnell Douglas, Lockheed, and Vought wind tunnels have a speed range up to Mach 5. NASA Langley and the Department of Defense Wright Laboratory both have high Reynolds number Mach 6 wind tunnels. Because much larger model sizes relative to test section dimensions can be tested at supersonic speeds, the Reynolds numbers noted are significantly higher than for subsonic and transonic wind tunnels;<sup>13</sup> however, the Reynolds numbers for complete supersonic aircraft configurations are at least twice as high as those noted above, which are based on root chord. A comparison of the Reynolds number capabilities of major subsonic, transonic, and supersonic wind tunnels is shown in Figures 7-5 through 7-7.

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<sup>13</sup> NASA, op. cit.



Source: National Aeronautics and Space Administration

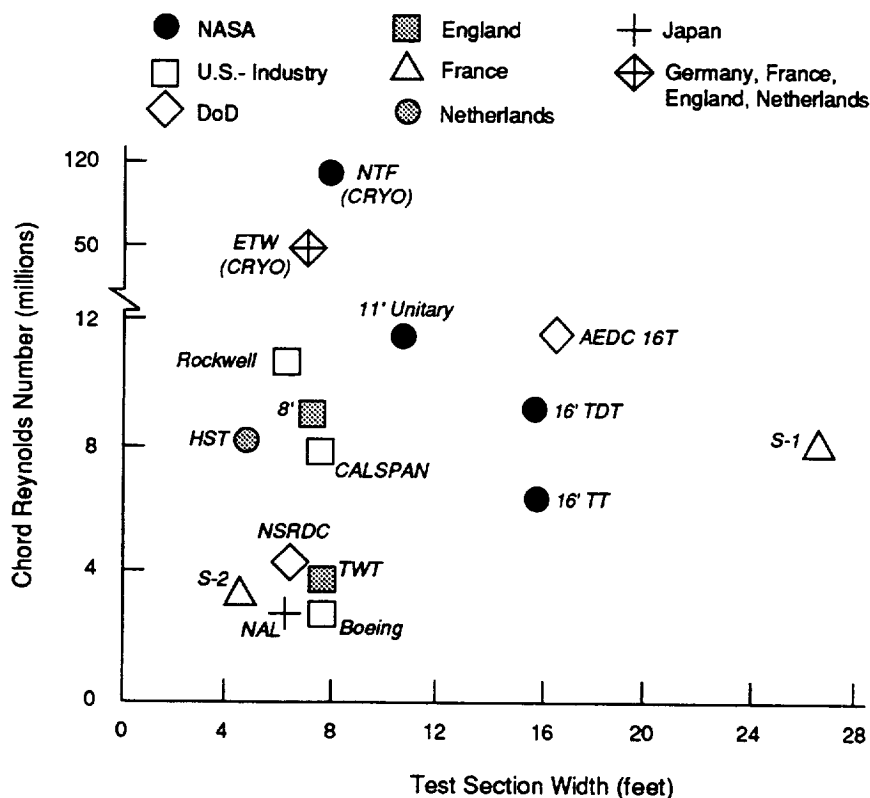
FIGURE 7-5 Comparison of major subsonic tunnels.

### Air-breathing Propulsion Facilities

Major air-breathing propulsion facilities can be divided into three categories: propulsion wind tunnels, altitude engine test facilities, and engine/propulsion component facilities.<sup>14</sup>

The wind tunnels are large facilities in which engine burn tests and propulsion/airframe integration tests can be run. A drawback of wind tunnels for engine testing is their inability to provide true temperature simulation over wide operating conditions. There are seven such tunnels in the United States including NASA Ames' 40' x 80' and 80' x 120', Lewis' supersonic 10' x 10' and 8' x 6', the Arnold Engineering Development Center (AEDC) supersonic 16T and 16S, and Boeing's 9' x 9'. Foreign tunnels include Canada's 10' x 20', France's transonic S-1, and the Netherlands' DNW.

<sup>14</sup> National Aeronautics and Space Administration. 1985. Aeronautical Facilities Catalogue. Volume 2. Airbreathing Propulsion and Flight Simulators (NASA RP-1133). Washington, D.C.



Source: National Aeronautics and Space Administration

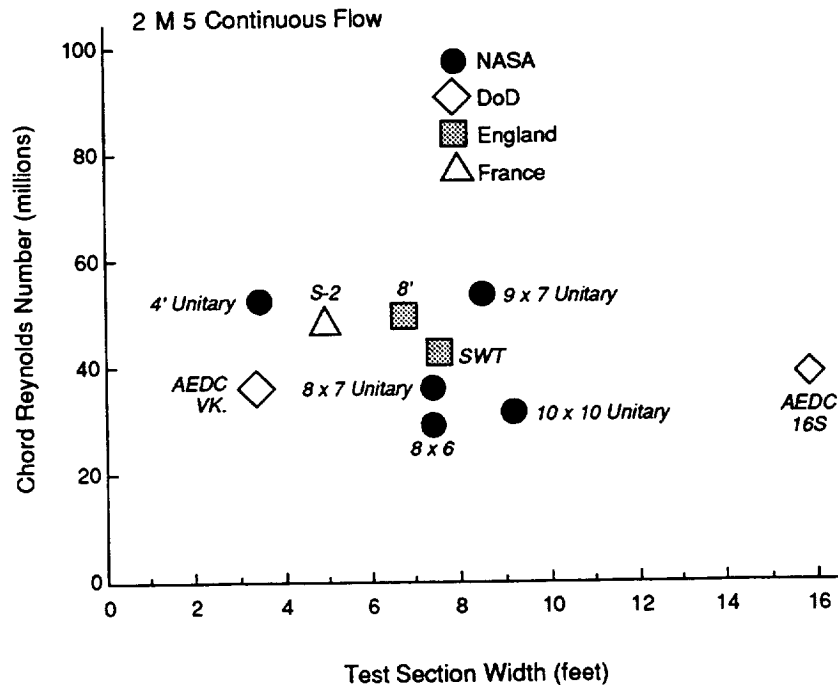
FIGURE 7-6 Comparison of major transonic tunnels.

Of some 60 altitude engine test facilities in the world, the one with the greatest capability by far is the AEDC Aeropropulsion Systems Test Facility with two 28-foot diameter cells, 85 feet long, mass flows exceeding 2,000 pounds per second, a broad temperature range, and speeds up to Mach 3.8.

There are 46 engine/propulsion component facilities in the United States for testing turbines, compressors, and combustors; the only foreign ones are in Japan and Belgium. These facilities are smaller and simpler than the other two categories.<sup>15</sup>

NASA owns approximately one-third of the major test facilities in the United States and one-fifth of those in the world. Most of NASA's facilities are more than 20 years old and are heavily utilized. Many are in need of repair, have marginal productivity, and need updated

<sup>15</sup> Ibid.



Source: National Aeronautics and Space Administration

FIGURE 7-7 Comparison of major supersonic tunnels.

control and data systems.<sup>16</sup> To overcome these deficiencies, NASA has undertaken a major facility revitalization program of which the first phase—returning them to operational status—is approaching completion. It is important that the revitalization program be continued to bring these facilities to the state of the art and then broaden their capabilities.

### Flight Test Facilities

The national flight research assets include the flight testing range and related ground facilities and the aircraft in NASA's research fleets stationed at Ames-Dryden Flight Research Facility, Ames-Moffett, Langley, and Lewis Research Centers. Current research aircraft are listed in Table 7-2.

<sup>16</sup> National Research Council. 1988. Review of Aeronautical Wind Tunnel Facilities. Washington, D.C.: National Academy Press.

TABLE 7-2 Current Research Aircraft

Center	Aircraft	Capability
NASA Ames-Dryden Research Facility	PIK 20E Sailplane General Dynamics F-16 Lockheed F-104 (2) Grumman X-29 McDonnell Douglas F-15 Eagle Boeing B-52 McDonnell Douglas F-18 Hornet Convair 990	Glider Supersonic Supersonic Supersonic high alpha Supersonic Transonic Supersonic Transonic
NASA Ames-Moffet Research Center	Bell XV-15 British Aerospace YAV-8B Harrier Boeing/DeHavilland QSRA Sikorsky UH-60 Blackhawk (2) Bell TH-1S	Tiltrotorcraft VTOL STOL Rotorcraft Rotorcraft
NASA Langley Research Center	Piper PA-28R Arrow Boeing 737-100 Learjet 28/29 Rockwell OV-10 Bronco	Subsonic Transonic Transonic Subsonic
NASA Lewis Research Center	DeHavilland DHC-6 Twin Otter Rockwell OV-10A Bronco	Subsonic Subsonic

### Test Requirements for Future Systems

Common to all speed regimes is the requirement for full-scale (high) Reynolds number facilities and flight capability, not only for high-lift devices and high-angle-of-attack configurations at low speeds, which are highly sensitive to Reynolds numbers, but also for conventional aircraft because of the emphasis on drag reduction. There is also a need for very accurate, nonintrusive instrumentation with high resolution for spatial and temporal measurements.

At low speeds the requirements are for flight and ground facilities to test takeoff and landing of conventional aircraft; high-lift devices (short-takeoff-and-landing vehicles), terminal area noise (engine, control surfaces, airframe); rotorcraft; and vehicles with expanded flight envelopes (e.g., high angle of attack). There is particularly strong emphasis on reducing the noise of flight systems, necessitating test facilities with very low background noise of their own.

In the transonic and supersonic regimes, large facilities are needed for propulsion/airframe integration and aeroacoustic studies. Also, low-disturbance supersonic

facilities and flight research aircraft are needed for laminar flow control and boundary-layer transition studies required for vehicles such as an HSCT.

Large air-breathing propulsion facilities are needed to test full-scale turbojet engines integrated into the airframe up to high supersonic speeds.

### **Adequacy of Existing Test Facilities to Meet Requirements**

#### **Low Speeds**

Such wind tunnels as NASA Ames' 80'  $\times$  120' and 40'  $\times$  80', the Dutch/German DNW, the U.K. 5 meter, and France's (ONERA) S-1 (8 meter) meet many of the low-speed test needs; however, none can meet the range of full-scale Reynolds numbers required. An important high Reynolds number capability will be added when NASA restores the Ames 12-foot Pressure Wind Tunnel to operate at 6 atmospheres and speeds up to Mach 0.6, but it will still be far short of the full-scale Reynolds number required. NASA Ames' 80'  $\times$  120' is well-suited for testing VTOL powered lift, full-scale rotorcraft, and high-lift devices for takeoff and landing, and is one of the few facilities suitable for full-scale high-angle-of-attack tests; however, it is limited to a Mach number of 0.15 and utilizes very large (full-scale) and, therefore, relatively expensive models.

For aeroacoustic testing, DNW offers the best capability to study noise generated by engines, airframes, and rotors. In the United States, consideration is being given, and an approach defined, toward fitting NASA Ames' 40'  $\times$  80' wind tunnel with a thick acoustic lining that will make it the largest facility capable of noise tests on full-scale aircraft and rotorcraft. However, this will not meet the requirements for research on noise reduction at higher climb-out and cruise/climb flight conditions, which are increasingly important challenges for the future.

#### **Transonic Regime**

The only facility with full-scale Reynolds number capability is NASA Langley's cryogenic National Transonic Facility with an 8.2'  $\times$  8.2' test section; however, its reliability and productivity to date have been relatively low. It is currently being upgraded. A major facility expected to become operational in the mid-1990s is the European Transonic/Cryogenic Wind Tunnel near Cologne, Germany. It will have a test section of 2.4 m  $\times$  2.4 m and cover the speed range from Mach number 0.15 to 1.2, with Reynolds numbers based on effective chord length up to 50 million, which is adequate to meet most future test requirements. Special attention in the development of the European Transonic/Cryogenic Wind Tunnel has been given to high productivity and reliability. The extreme cooling to cryogenic temperatures of models and instrumentation used in these facilities imposes special requirements and handling techniques.

### **Supersonic Regime**

Although several supersonic wind tunnels have a Reynolds number capability (based on model size) exceeding 100 million, these are based on wing sections, which are rather large relative to tunnel dimensions, and not the full vehicle. None of these facilities reach the full-scale Reynolds numbers needed for a HSCT or supersonic military systems. In terms of low-disturbance supersonic wind tunnels to study laminar flow control and boundary layer transition, NASA presently has in operation a Mach 3.5 tunnel and is developing a new facility with Mach 3.5 and Mach 6 nozzles. Other low-disturbance wind tunnels are being planned. For supersonic laminar flow research, flight test aircraft play a vital role in technology development and validation by providing access to the real atmospheric disturbance environment. In addition, it is important that large-scale aircraft be available for laminar flow research to provide answers to critical high Reynolds number issues.

### **Air-breathing Propulsion**

The Aeropropulsion Systems Test Facility at the Arnold Engineering Development Center provides a unique capability for full-scale propulsion/airframe integration and combustion tests up to Mach 3.8. Other engine test facilities are inadequate to meet future full-scale requirements. However, one should bear in mind that, even in the Aeropropulsion Systems Test Facility, only segments of a complete vehicle can be tested but these would include parts of the airframe as well as the engine.

### **Computational Fluid Dynamics**

Computational fluid dynamics has become an increasingly important complement to wind tunnels as a tool in the design of new aircraft. Each does different things best. Together they provide more detailed and complete information than wind tunnels alone. This vital role for CFD stems from the tremendous advances over the years in speed and memory size of supercomputers, as well as improvements in numerical algorithms. Among current supercomputers, the Cray 2 has an effective speed exceeding 200 million floating point operations per second (MFLOPS). The more recent Cray YMP has four times that speed (i.e., about 1,000 million floating point operations per second MFLOPS).

Comparable advances are projected to continue for several years, and it is important that they be channeled toward facilitating the application of CFD to airplane design. Experience gained by the airframe industry in the utilization of CFD in recent years has served to identify areas of future development in computational technology.

In the early 1980s NASA undertook the development of a Numerical Aerodynamic Simulation facility as a means of providing a continually updated capability with the latest available high-speed processors, for the purpose of solving the basic flow equations and with the intent of enhancing the application of CFD to aerospace vehicle design. Achievement of these goals requires a refocus of objectives. In the area of hardware—mainframes, communications,



and workstations—NASA's Numerical Aerodynamic Simulation facility has had a pathfinding role and is positioned to continue as such.

In the area of algorithm research and code development, the main focus in the past was principally on solving increasingly complex and complete forms of the basic flow equations. In the future, the focus needs to be expanded to include other factors that are essential toward the effective application of CFD to airplane design. In particular, there is a need for CFD capabilities that

- can handle the flow about arbitrary geometries;
- resolve all the important physical length scales;
- provide reliable accuracy, when used by a design engineer, with sufficient credibility to support engineering decisions;
- can be rapidly set up and executed (in one day or less); and
- are economically viable (i.e., the real computing costs for the tens or hundreds of runs typically needed to solve a design problem are justifiable and acceptable).

It is expected that the next decade will witness the emergence of CFD as the critical technology for aerodynamic design. There should be a dramatic change and shortening of the design process, which will enhance and enable concurrent engineering and the optimization of air vehicle systems in terms of overall economic performance. This will require a significant advance in CFD algorithm research and code development.

Such developments are heavily dependent on a close working relationship between NASA and the aeronautical industry to enhance the relevance of NASA research and enable a rapid translation of research advances into application to the design process.

### **Recommendations for Test and Computational Facilities**

This section of this report defines a course for NASA, industry, and academia to achieve competitiveness in aerodynamics. Specific investment needs are described to strengthen the U.S. science and engineering infrastructure and technology validation efforts. The fact that critical technology initiatives planned by NASA and industry have not been implemented demonstrates that the problem is not a lack of ideas and plans but, rather, the priority given to aeronautics.

Experimental facilities and methods, along with computational capabilities, comprise the infrastructure upon which advances in technology can develop and flourish. The future ability of the United States to remain competitive in aeronautics is directly dependent on the quality of its experimental and computational facilities, which, along with flight testing, are the design tools for new aircraft. Economic and technical compromises must be made to determine where each of these tools fits into the design process. The three must serve in a complementary fashion, and the extent of use of any one of them is dependent on its ability to provide certain types of data more effectively than the other two. Finally, precompetitive technology validation through cooperative efforts among government, industry, and academia must be substantially increased if the United States is to remain competitive in aeronautics.

The key aerodynamic technologies that require increased investment for competitiveness include

- aerodynamic cruise performance, including subsonic and supersonic laminar flow control technology;
- aircraft propulsion/airframe integration for both subsonic and supersonic aircraft;
- low speed and high lift for subsonic configurations, including wake mechanics, wake vortex, and measurement technology;
- computational fluid dynamics for aircraft design, including validation of codes;
- low speed and high lift for supersonic configurations; and
- aerodynamics of rotorcraft.

Throughout this report, references are made to needs for a variety of improved ground and flight experimental and computational capabilities. It is important that NASA receive the support and direction required to provide the United States with experimental and computational capabilities that will enable the aeronautical community to develop competitive or superior products in all flight regimes.

The following are specific ground-based experimental capability recommendations to NASA:

- To vigorously pursue its facility revitalization program beyond the present phase, toward raising its facilities to the state of the art and then broadening their capabilities.
- To generate an intensive program to develop high-resolution, nonintrusive instrumentation for spatial and temporal measurements.
- To proceed with all haste in fitting its Ames' 40'  $\times$  80' wind tunnel with an acoustic lining essential for noise testing on full-scale vehicles.
- To develop a low-speed, low-disturbance test capability that can operate at full-scale Reynolds number (based on chord length of at least 50 million) in the range from Mach number 0.1 to 0.5. Because of dimensional constraints, such a facility would have to be pressurized; also, consideration in its design might be given to the possibility of using heavy gases instead of air for aeroelastic scaling or as a means of boosting Reynolds numbers to the required values. Mixtures of heavy gases in proportions to provide the proper scaling of physical variables have been successfully used in testing turbine and compressor stages at realistic conditions of engine operation. A possible alternative to using a heavy gas as test medium would be to operate with air at moderate cryogenic temperatures—down to -150°F—based on the experience gained in operating the National Transonic Facility.

- **To develop a supersonic, low-disturbance test capability that can operate at a full-scale Reynolds number of 400 million to 500 million over the range from Mach 2 to 6 to meet test requirements for an HSCT and military systems. A pressurized test section would be needed to meet the stringent Reynolds number requirement.**

The first important point regarding facilities in general is to ensure high reliability because it is crucial to the value of their data, but good productivity must also be ensured by adequate staffing and by efficient means of moving test models in and out of tunnels. Furthermore, data acquisition and processing equipment must be upgraded periodically to keep these valuable test capabilities current.

**Regarding aeronautical flight experimental capabilities, NASA should (1) vitalize the flight research capability and in-flight technology validation efforts in all speed regimes, and develop advanced measurement technologies for flight research.** To carry out these recommendations for flight capability, NASA must structure the management of flight efforts to strengthen the integration of flight and ground-based research. NASA must plan for the future requirements for flight to include experimental aircraft, platform test-bed aircraft, and ground and flight infrastructure capabilities.

Finally, in the area of computational technology it is essential that NASA, on a continuing basis, *acquire and maintain state-of-the-art computing hardware and develop the CFD algorithms and software* that are key to the application of computational technology to aerodynamic design. This includes an aggressive pursuit, with the input of industry, of advances in the development and verification of both design and analysis CFD codes.

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## 8

### PROPULSION

#### INTRODUCTION

Propulsion technology offers the greatest single contribution to the improvement of cruising economy and the environmental impact of commercial aircraft. The past three generations of gas turbine engines have incorporated increased turbine inlet temperature, increased compressor pressure ratio, increased bypass ratio, improved fan and nacelle performance, reduction of noise and emissions, and improved reliability that led to a continued dominance of the world commercial aircraft market. This pace of development in new engine technologies, together with advances in engine-airframe integration, can, with adequate support from industry and the National Aeronautics and Space Administration (NASA), be continued over the next 10 to 20 years, thus providing superior propulsion systems entering service through the 2005–2015 period.

These gains rest, of course, on continued development of new and improved materials and material-processing techniques, the clearly available advances in turbomachine technology, promising progress in combustion technology, and vastly improved utilization of computational fluid dynamics (CFD) in engine design procedures. Finally, there is the unknown impact of novel technologies, such as "smart engines" and magnetic bearings, that may completely change the course of engine development.

This wide range of possibilities for engine development is narrowed by the general type of commercial aircraft to which they will be applied. The specific requirements differ between the advanced subsonic transports, the high-speed civil transport (HSCT), and the short-haul class of aircraft. Although these engine classes have many features in common, each has unique criteria that have a major influence on its design.

In light of the factors mentioned above, one section of this chapter is devoted to the energy efficiency, economy, and environmental goals of the engines appropriate to each of the aircraft types. Sections are then included dealing individually with technological issues that require discussion in greater detail. The boxed material summarizes the primary recommendations that appear throughout the chapter, with specific recommendations given in

### Recommendations

#### General

NASA must vastly strengthen its propulsion technology program to include:

- much greater emphasis on subsonic transport propulsion systems where the United States has lost its technological edge over foreign competitors;
- continued support for the HSCT propulsion program; and
- a strong, broad-based propulsion technology program to position the United States for the post-2000 short-haul markets, including a better balance between vertical takeoff and landing commuter systems and conventional systems.

#### Specific

1. NASA should increase its support for generic computational and experimental propulsion research. In addition, NASA must lead in the development of technical communication with industry in computational science applied to propulsion.
2. NASA should take the initiative in setting up a joint NASA/industry program for innovative subsonic propulsion technology that is at least equivalent to the NASA/industry HSCT propulsion program.
3. NASA must support the development of specialty materials not currently available as commodities that, if properly developed, will become common in aircraft engines.
4. The basic research effort at the Lewis Research Center (LeRC) in low nitric oxide combustors for the HSCT has produced excellent results and the momentum should be maintained. NASA should put in place the planned Joint Technology Acquisition Program between LeRC and industry.
5. NASA should take advantage of its unique position to mount a substantial program in active control technologies for aircraft engines.
6. NASA's turbomachinery research program, should be strengthened to the point at which NASA can recapture its leadership role.
7. NASA's LeRC should direct increased effort toward the enabling technologies in compressor, combustor/turbine, and control accessories for engines appropriate to short-haul aircraft.

order of priority, and the benefits that are possible with adequate research and development effort in propulsion.

### PROPULSION FOR ADVANCED SUBSONIC AIRCRAFT

Advances in propulsion system technology have been the prime source of subsonic transport performance improvements for more than 30 years and this trend has continued through

**Benefits of Research and Technology Development in Propulsion****Engine Performance**

- Reduced engine fuel consumption
- Reduced emissions
- Reduced engine noise
- Reduced engine weight
- Greater engine thrust
- Enhanced reliability
- Reduced maintenance requirements
  - Long-life materials and components
  - Design for maintenance

**Engine Design and Development**

- Shortened development cycle
  - Improved computational capabilities for propulsion
  - Improved testing facilities for propulsion
- Technology validation

the evolution of high bypass turbofans. Engine fuel consumption has improved more than 40 percent from the early turbojets; even within the high bypass class, Pratt & Whitney (P&W), Rolls Royce, and General Electric (GE) engines have improved by 16 percent since 1970. Size is a major factor in aircraft productivity and in fuel burned per seat-mile, and the growth in engine thrust has been a major contributor to aircraft size. The high bypass turbofans of 40,000 pounds force (lbf) thrust ushered in the jumbo jet era, and engine growth to 50,000–60,000 lbf thrust has led to even larger, more capable aircraft. Outstanding improvement in engine reliability has resulted in long-range (over water) twin-engine aircraft with engines of 75,000–85,000 lbf thrust under development for mid-1990s service. Growth to 90,000–100,000 lbf thrust is expected.

**State of the Art**

The state of the art in new large engines is characterized by an installed propulsion system cruise-specific fuel consumption of 0.54–0.56, including nacelle drag but not customer bleed. The installed thrust-to-weight ratio is about 4.5. Cycle pressure ratios are 36–38; the compressor discharge air temperature is 1250°F; and the turbine rotor inlet gas temperature is 2550°F, with the mechanical design redline 150°F higher. Materials include fourth-generation nickel superalloys, high-strength titaniums, and carbon composites. Controls are digital. Most turbomachinery component efficiencies are 90–92 percent; compressors have greater than 87 percent polytropic efficiency. Large engine fans are 8–10 feet in diameter; fan inlets and cowls

are 11–14 feet in diameter and 15–18 feet long. Prices for large engines are around \$100 per pound of thrust, and because of intense competition, industry will make major efforts to reduce this. In the 1990s this technology can be expected to evolve to 50:1 cruise pressure ratio, with turbine inlet temperatures up 100–150°F as further materials improvements are made. Refinements will continue to be made in component performance, nacelle performance, and weight.

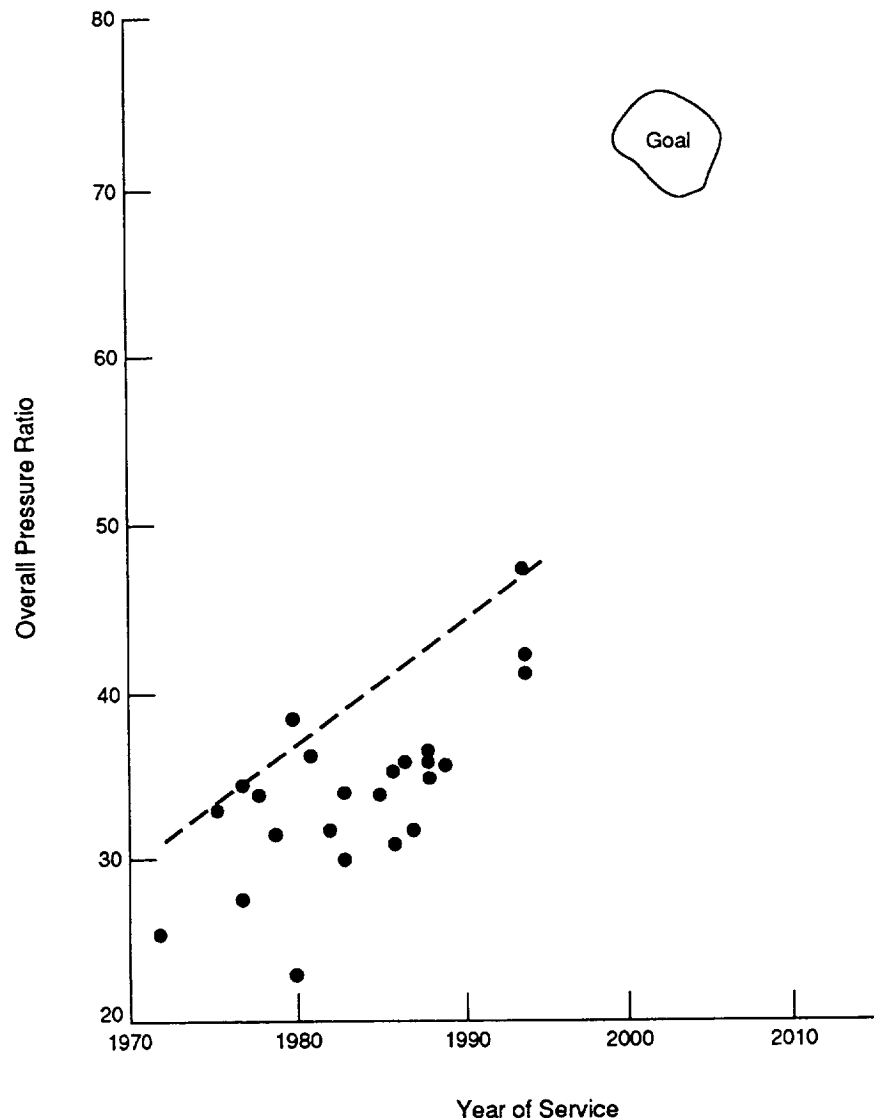
At this point it is worth mentioning a program that exemplifies the type of joint NASA/industry cooperation that can have significant impact on the state of the art and on the overall competitiveness of U.S. products. The Aircraft Efficiency (ACE) program was begun in the 1970s in response to the energy crisis and contained six separate programs aimed at producing real improvements in the efficiency of aircraft. One of the six ACE programs, the Energy Efficient Engine (E<sup>3</sup>) program, had a goal of 12 percent reduction in engine fuel consumption. The program ran from 1977 to 1982 and was jointly funded by NASA, GE, and P&W. The goal was met and, most importantly, both GE and P&W have aggressively incorporated the component and systems technology that resulted from the E<sup>3</sup> program into their current generation of engines, including the GE CF6-80 and the P&W 4000 engines. Also, the GE-90 engine that will be certified in 1994 is very closely related to the engine that was developed and tested during the E<sup>3</sup> program. The Committee believes that this type of program can provide tremendous benefits to the U.S. aeronautics industry and should be pursued wherever feasible.

### **The Future**

In 1989, NASA Lewis Research Center (LeRC) sponsored initial preliminary design studies of a new class of high thermal efficiency, high propulsive efficiency engines. Pressure ratios of 75–100:1 and turbine rotor-in temperatures of 3000–3400°F were explored, using new materials and technologies, for the post-2000 period—far beyond the evolution expected in the 1990s. From this initial work it is apparent that there could be one block of new technology readied in the next 10 years for service around 2005 and a second block, less defined at this time and more dependent on new fiber-reinforced materials, that could be available about 10 years later for service in 2015. Both would permit dramatic advances. The first (2005), would yield a 15–20 percent reduction in fuel burned by mid-1990s engines, resulting from reduction in fuel consumption and reduction of propulsion drag and weight. The aircraft direct operating cost (DOC) could be reduced by 8–10 percent (at a fuel price of \$1.00 per gallon). The second (2015) could lead to 30 percent reduction in fuel burned and 12–15 percent DOC reductions from mid-1990s levels. These advances are greater than the high bypass turbofans of the late 1960s.

To achieve these results, higher core engine thermal efficiencies and higher propulsive efficiencies must be combined with improved nacelle and installation technology—all at lighter weight and at affordable costs. Figures 8-1 to 8-3 show trends in pressure ratio, compressor exit temperature, and turbine inlet temperature, respectively. The factors contributing to these three items are summarized in Tables 8-1, to 8-3.



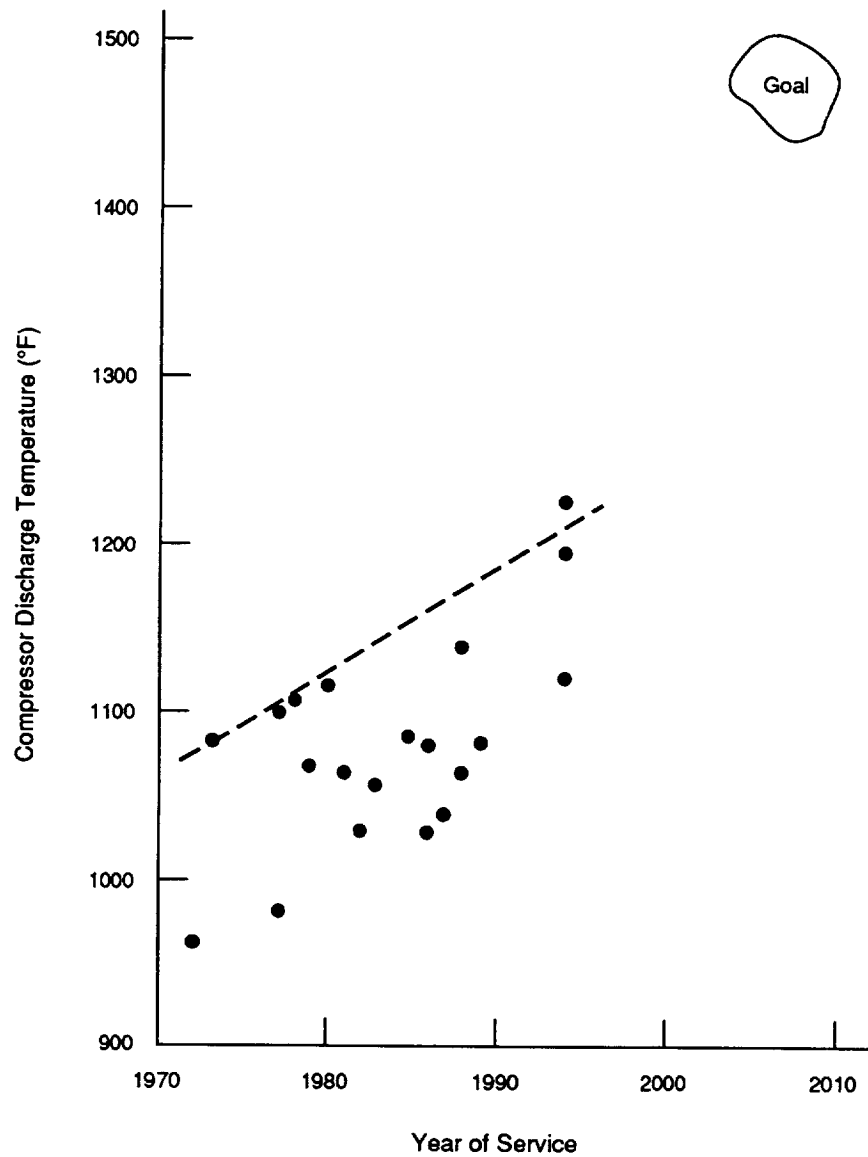


Source: General Electric

FIGURE 8-1 Overall pressure ratio for high-bypass ratio turbofans, maximum climb.

The core engine technologies that are key to the improvements listed in Table 8-2 are

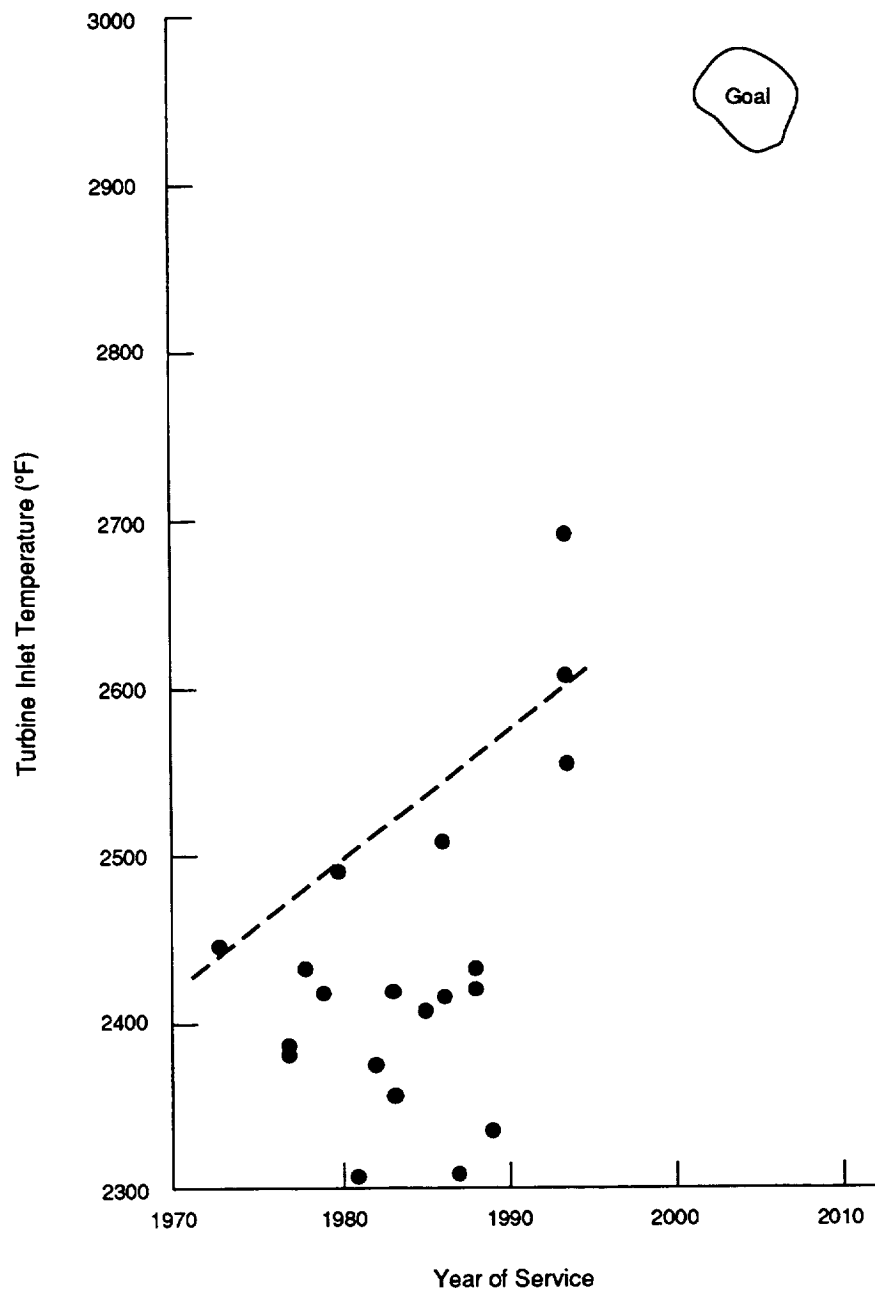
- improved metal materials, coatings, and fabrication techniques (2005);
- new engineered materials such as titanium metal matrix composites (MMCs), titanium aluminides, and nickel aluminide (2005);
- fiber-reinforced metal and ceramic high-temperature materials (2015);
- more efficient turbine blade cooling; possibly cooling air coolers;



Source: General Electric

FIGURE 8-2 Compressor discharge temperature for high-bypass ratio turbofans, sea level static.

- advanced, more efficient, high-speed turbomachinery;
- turbomachinery with "smart" controls (2015); and
- combustors to reduce takeoff emissions.



Source: General Electric

FIGURE 8-3 Turbine inlet temperature for high-bypass ratio turbofans, sea level static.

The corresponding keys to providing the improvements in low pressure systems as shown in Table 8-2 are

TABLE 8-1 Factors Providing Improved Core Thermal Efficiency

	2005 Service	2015 Service
<b>Higher cycle pressure ratio</b>	60–75	> 75
<b>Higher turbine rotor-in temperature</b>	2900–3000°F	3200–3400°F
<b>Higher component efficiencies</b>	1–2 %	2–3 %
<b>More efficient customer power and bleed extraction</b>	Advanced ECS	Power by wire

TABLE 8-2 Factors Providing Improved Propulsion Efficiency

	2005 Service	2015 Service
<b>Higher fan efficiency</b>	2 %	2–3 %
<b>Higher fan turbine efficiency at higher loadings</b>	1 %	2 %
<b>Increased bypass ratio</b>	Yes	Yes

- integrated fan aeroacoustics for higher efficiency and lower source noise;
- advanced materials for higher-temperature, lighter-weight fan turbines;
- composite fan blade development;
- advanced gearbox systems employing new materials, bearing technology, and lubricants;
- simpler higher-reliability variable pitch actuation systems; and
- lower-cost designs and manufacturing.

Current engines have bypass ratios of 5–6 at fan pressure ratios of 1.65–1.8. With the higher turbine temperatures of the post-2000 period we must explore a range from direct-drive, mixed-flow, high-bypass turbofans (1.55–1.7 fan pressure ratio, 8–10 bypass ratio) to geared-drive, very high bypass engines (1.35–1.4 fan pressure ratio, 15–20 bypass ratio) with fixed-pitch fans and variable-pitch reversing fans. The range of engines and applications should also include advanced gear and turbine-driven unducted fans (1.1 fan pressure ratio and 35–50

TABLE 8-3 Improvements in Nacelle and Installation Technology

	2005 Service	2015 Service
<b>Reduced fan cowl drag</b>	2 %	More ?
<b>Eliminate interference drag</b>	Yes	Yes
<b>Better acoustic treatment — less noise</b>	Yes	Yes
<b>Weight reduction</b>	Yes	Yes
<b>Integrated advanced ECS and laminar flow suction system</b>	Yes	Yes

ultrahigh bypass ratio). As bypass ratio increases and fan pressure ratio decreases, specific fuel consumption improves but fan diameter increases dramatically. Nacelle and installation drag increases and weight increases. The low-pressure fan, fan turbine system, and the composite lightweight nacelles weigh two-thirds of the entire system in today's power plants. In past studies, such trends increased cost, eroded most of the fuel efficiency benefits, and drove up the direct operating cost. The question for the future is whether new gearbox, acoustic, and nacelle technology can shift the optimum bypass ratio for better economics at lower noise. Given the state of the art of large gearboxes, it seems questionable that engines of 15–20 bypass ratio would first enter service in the 60,000–100,000 lbf thrust category or for any long-range twins over water. The same holds for unducted ultrahigh bypass ratio turbofans, which have the lowest fuel burned potential. In neither case should this discourage very careful examination of their potential for the 2005 and 2015 periods.

The keys to providing these improvements in nacelle technologies are

- integrated nacelle, wing and fan aeroacoustic development;
- advanced mixers;
- smart controls;
- advanced composites and lighter-weight integrated nacelle, reverser, and fan structures;
- laminar flow nacelle;
- advanced aircraft environmental control system; and
- lower-cost designs and manufacturing.

Future noise reduction is possible but must be balanced with economic improvements. Source noise reduction combined with advanced nacelle acoustic features is necessary. An aggressive target is 10 dB below Federal Aviation Regulation (FAR-36) Stage III restrictions.

### **Observations for Advanced Subsonic Aircraft**

It is clear that through both innovation and evolution in the twenty-first century, propulsion will provide technological improvements to transport aircraft equal to those accruing from aerodynamics, materials and structures, and active controls combined. Very large gains can be made in performance, weight, noise, emissions, and operating costs.

U.S. engine products have the greatest share of the large subsonic propulsion market—about 80 percent in 1990—but the United States no longer has a technology edge.

The U.S. propulsion industry is focusing on the next 10 years—the next new products and derivatives. Manufacturers have committed billions to research and development in the 1990s and to improved manufacturing capabilities. They have few financial resources left to undertake the high-risk, high-payoff technologies for advanced post-2000 products.

The subsonic transport market, which is by far the largest, the most certain, and the most competitive, receives disappointing support from NASA. There is no evidence of a coherent, comprehensive approach. Only a few selected elements of subsonic technology are under way or in planning, and these mostly in-house. There are no goals for maintaining a competitive edge.

The investments made by NASA in subsonic propulsion technology through joint NASA/industry programs in the 1975–1983 period were very effective. The 1989 preliminary design studies with engine companies on high thermal efficiency and advanced materials were a good start, but small and with no follow-on. This valuable type of investment has been drastically reduced over the last eight years and, as a consequence, NASA is not playing a strong "pathfinder role" in subsonic propulsion technology.

### **Recommendations for Advanced Subsonic Aircraft**

It is the belief of the Committee that the technology for subsonic transport propulsion must be vastly strengthened; there is great opportunity here. **To do so, NASA should take the initiative in setting up a joint NASA/industry program for innovative subsonic propulsion technology that is the equivalent of the NASA/industry HSCT program.** There is no reason to do less.

The first step should be to set up a vigorous preliminary design activity for aircraft propulsion systems—again, the equivalent of what has been underway for HSCT. Systems for two time frames should be examined: year 2005 service and year 2015 service. Improvement goals for fuel burned, DOC, noise, and emissions should be set. Firm conclusions can be reached regarding benefits and the definition of key high-risk/high-payoff technologies described earlier in this section. Programs for enabling technologies can then be planned.

One of the greatest benefits of this preliminary design effort is that it would get the aircraft industry, the propulsion industry, and NASA working together as a team to address high-risk, high-payoff technology in a disciplined system context, 15 years before products are expected.

## PROPULSION FOR HIGH-SPEED CIVIL TRANSPORT

The HSCT's three key requirements, on which the NASA/industry program is focused, are economic viability relative to advanced subsonic transports of the same time period, FAR-36 Stage III noise standards, and insignificant depletion of stratospheric ozone. The consequent principal challenges to the propulsion system are price and fuel consumption, weight and noise, and emissions. Engine weight and noise go together because the thrust level and jet velocities are fixed by the aircraft's takeoff and supersonic cruise characteristics. The engine contenders are in the 650 pounds per second airflow, and 50,000–60,000 lbf thrust class. The HSCT will probably require four such engines, with takeoff jet velocity in the range of 2,400 to 3,000 feet per second.

Four candidate engine types which are being sorted out by the preliminary design process:

1. a turbine bypass engine—basically a single spool turbojet with a "variable cycle bleed" of compressor air around the turbine; this engine would use an ejector nozzle to entrain another 100 percent or so of air to mix with the engine exhaust during takeoff; additional suppression features are included;
2. a mixed-flow turbofan similar to U.S. Air Force/U.S. Navy fighter engines, but with two-dimensional ejector nozzle of more than 60 percent extra air entrainment, mixers and suppression features;
3. a variable-cycle engine of the general sort that GE flew in the U.S. Air Force (USAF) Advanced Tactical Fighter prototypes, but with higher bypass and a two-dimensional ejector/ mixer/suppressor nozzle; and
4. a version of the mixed-flow or variable-cycle engine with special fan features for bringing additional air aboard.

Generally, these engines have cycle pressure ratios between 20:1 and 25:1, consistent with compressor discharge temperatures of about 1250°F, which is an important consideration for long-life supersonic cruise. Takeoff turbine temperatures will be 2900–3000°F, with redline design temperatures 100–150°F higher, and supersonic cruise temperatures about 2700°F. Engine controls will be advanced digital.

To meet the FAR-36 Stage III requirements it is necessary to bring aboard a large additional amount of air during takeoff to reduce high-velocity jet noise through mixing or shielding, in addition to mechanical noise suppression devices. These features add a great deal of weight. The total gross weight penalty charged to propulsion noise reduction is 50,000–100,000 pounds with current concepts. The larger fuel consumption associated with the

HSCT adds an additional 8,500 pounds for each 1 percent increase in specific fuel consumption (sfc). It is anticipated that the supersonic cruise sfc will be 1.23–1.3 and the subsonic sfc 0.88–0.95. Weight is also challenged by the requirement for the HSCT engine to spend most of its life at high supersonic cruise temperatures. To keep weight in line, the engine and the jet nozzle are being designed around an advanced group of new materials. Without these, engine weight would escalate by 20 percent and fuel consumption would increase accordingly.

Current estimates of engine weight, including a 4,000–5,000-pound jet nozzle, are in the range of 11,000–12,500 pounds, but much design effort, and materials and noise research are required to establish the weight with confidence. Present weight uncertainty is probably about 2,000 pounds per engine; an extra 1,000 pounds of weight in each engine would add approximately 24,000 pounds of takeoff gross weight.

Reducing nitrogen oxide ( $\text{NO}_x$ ) emissions from an index of 40 g/kg fuel or so to the current index target of 5 g/kg fuel involves a completely new combustor design, new materials, and a major research and development program. There are two concepts, each fundamentally sound in its principle of  $\text{NO}_x$  reduction. Early progress is encouraging.

NASA and industry recognize these major HSCT challenges and are concentrating the early phases of propulsion work on aggressive noise, emissions, and materials programs.

Much of the turbomachinery technology involved is well grounded in previous and current military programs for low bypass turbofans and variable-cycle engines and in recent progress in improving component efficiencies of subsonic transport engines. Integrated supersonic inlet, basic engine, and jet nozzle work is critical for optimizing supersonic performance.

In general, there appears to be less risk in meeting goals for specific fuel consumption than in other challenges mentioned previously. It is important to note, however, that the fuel burned per passenger seat per trip will be somewhere between 2.5 and 3 times that of improved/advanced subsonic transports and that to ensure economic competitiveness, this factor must be offset by increased productivity of the aircraft.

The price of engines and engine parts is a function of the manufacturing cost and the amortization of the development, certification, and flight test program costs required to ensure commercial guaranteed performance and to meet commercial standards of safety, reliability, durability, and maintainability. The prices will be well above the \$100/lbf thrust of current 60,000 lbf thrust subsonic engines, and the development cost will probably be several times that of a subsonic engine, perhaps \$3 billion to \$5 billion. P&W and GE have teamed together on the HSCT propulsion program in order to pool resources, maximize progress for the funding available, and bring more ideas and talent to bear on the challenges.

### **Propulsion Technology Challenges**

The Committee has identified the following challenges that must be faced to meet the propulsion needs of the HSCT:



- Turbomachinery
  - Fan, compressor, high-pressure turbine, low-pressure turbine efficiency improvements through CFD and experimentation
  - Inlet, engine, control systems compatibility; operability
  - Turbine life and cooling
  - Component reliability
- Combustor
  - Development of a viable commercial design: new fuel injection, mixing, variable geometry, and high-temperature walls with new ceramic matrix composite (CMC) materials
  - Validation of technology readiness
  - Combustor reliability and life
- Jet nozzle performance, acoustics, durability
  - Effective ejector systems
  - Jet mixing
  - Chute and mixer suppressor technology
  - Acoustic suppressor lining for jet nozzles—CMC material
  - Thrust reversing
  - Nozzle coefficients exceeding 0.98 at cruise, including leakage
  - Actuation systems
  - Validation of technology readiness
  - Nozzle reliability and life
- Materials
  - A family of six new materials: highest risk are CMCs for combustor and jet nozzles; somewhat less risky—but vital for weight and life—are fan, compressor, and turbine materials
  - Validation of technology readiness
- Advanced digital controls
  - Must handle twice the functions of current commercial turbofans
  - Maximize performance, operability, life, reliability, and maintainability

- Weight
  - Very careful, comprehensive, and clever mechanical design to accommodate new materials and jet nozzle/acoustics technology
- Manufacturing technology
  - Large components using new materials
- Long-term HSCT growth
  - CMC turbine blade materials and higher turbine temperatures, smart engine/controls for inlet/fan/compressor weight savings.

### **Observations for High-Speed Civil Transport**

The Committee was very impressed by the major joint NASA/industry propulsion effort on the HSCT, funded mainly by NASA. In fact, the primary features of this collaboration could serve as a model for other technology development efforts:

- It is a high priority effort.
- NASA is playing the leadership role.
- It is a carefully planned and focused effort.
- It has a well-established timetable that is flexible enough to account for unexpected results.
- Vigorous preliminary research and design work has been done.
- There is excellent and enthusiastic teamwork among the LeRC, P&W, and GE.

The Committee believes that high-speed research is well funded through Phase I of the HSCT program, but that adequate technology validation will be an important issue in the 1997–2000 time frame.

Many major problems remain to be solved, including engine/nozzle noise, engine emissions, and the advanced materials such as CMCs for the combustor and nozzle that will be required to make the HSCT viable. Also, efforts to maintain the weight of the propulsion system and keep the cost of the systems to a reasonable level must be addressed. Furthermore, there are some important uncertainties that are beyond the control of either NASA or industry. These include problems in defining and alleviating concerns about ozone depletion, stratospheric pollution, and global warming, and the price of fuel in the early parts of the next century. The Committee believes that NASA has good programs under way for most of these concerns, but definitive results may be years away.

An important determination that has yet to be made, is a preliminary evaluation of the economic competitiveness of an HSCT compared to new and improved long-range 400–800-seat

subsonic transports of the 2005 period and beyond. Clearly, without a compelling economic reason to proceed with the development of the HSCT, it—like the supersonic transport—will run the risk of being a technological success but an economic failure. If such an economic justification exists, the development of a successful HSCT without U.S. leadership will severely affect the overall competitiveness of the U.S. aircraft industry. **Thus, it is extremely important to maintain an adequate design and research and development program to establish the viability and technology readiness of the HSCT concept.**

### **Recommendations for High-Speed Civil Transport**

**The Committee recommends that NASA:**

- 1. NASA should continue to maintain an adequate design and research and development effort within the HSCT program.** Problems yield to creative effort and new knowledge from research. The key work is still in an early stage.
- 2. NASA should broaden the preliminary design program to include serious evaluation of alternative HSCT systems with lower overall propulsion risks and penalties:**
  - Operate lower in the stratosphere. Reduce stratospheric NO<sub>x</sub> emissions by cruising at Mach 1.6–2.0 below 50,000-foot altitude.
  - Increase cruise lift-over-drag (L/D) ratio as far beyond 9 as practical through increased span, laminar flow control, etc. Include consideration of oblique wing configurations with L/D ratio of 13. The aerodynamic design of the vehicle will be more difficult, but the size and weight of the propulsion system will be reduced.
  - Make special additional efforts to enhance takeoff lift, thereby reducing takeoff thrust requirements and allowing lower specific thrust cycles with less jet noise suppression.
  - Make a very careful study of three-point noise trade-offs. Consider raising the airport sideline noise a few decibels and doing better than FAR-36 Stage III at the other two stations. Overlay noise contours on communities near airports where HSCTs will operate. See whether large propulsion risks and economic penalties can be reduced.
- 3. NASA should include growth studies in the preliminary design program.** The HSCT is less flexible than subsonic aircraft when it comes to growth and derivatives. How will the range be increased to 6,500 miles; how are additional passengers accommodated; what new technologies are involved?
- 4. NASA should invest more effort in establishing preliminary prices for economic evaluation.**

## **PROPULSION FOR SHORT-HAUL AIRCRAFT**

The current fleet of short-haul or regional transports covering the 19–50 passenger market has undergone dramatic changes over the past 10 years as a result of airline deregulation. Deregulation in Europe is expected post-1992. Most scenarios suggest three large, major airlines and three to five midsize and niche players by the year 2000—all having absorbed the regional carriers to support the behemoth hub-and-spoke systems. In general, this points to larger, route-tailored aircraft with particular emphasis on cost of operation and passenger comfort. Also, the large projected increase in passengers will drive simultaneous adjustments in airline route structure, aircraft performance, and airport infrastructure.

### **40–75-Passenger Aircraft Market to 2005**

The 40–75-passenger market is poised for the largest adjustment in the short-haul market. As the stress on the infrastructure of the hub-and-spoke system has grown, regional carriers have reacted aggressively with a trade-up to aircraft for more than 40 passengers. The trend is expected to continue, with sales of 40–75-passenger regional transports exceeding 2,500 units over the next 10 years.

Regional transport equipment in the future will follow the existing trend toward a new generation of 100–200-passenger transport airplanes. The trend is to use higher aspect ratio wings and very high bypass (VHB) turbofan power (bypass ratio  $> 10$ ). During the 1990s, regional transport for more than 60 passengers will move toward jet transport using higher bypass-ratio turbofan engines to provide the best overall solution for fuel efficiency, high speed, low noise, lower emissions, and superior cabin comfort and ride. Operationally by 2005, the 40–75-passenger machines will be predominantly jet transports using high-bypass or VHB turbofans.

### **19–35-Passenger Aircraft Market to 2005**

To carry fewer than 40 passengers, the most efficient propulsion system for the regional transport will likely remain turboprop-powered aircraft, which will continue to serve routes of less than 300 nautical miles. However, the airframe and the engine must be uniquely designed for the needs of the regional transport, rather than being a derivative of today's military and general aviation turboprop/turboshaft engines. These new airframes and engines must focus on reducing the cost of operations by 20–30 percent by 2005, with moderate improvements in fuel efficiency (10 percent per decade).

### **Long-Term Regional Aircraft Market (2005–2020)**

Gradually, the demarcation between regional carriers of 10–75 passengers and the new wave of 75–130-passenger VHB jet transports will disappear, and a fully integrated system of

modern aircraft will service the short-haul market with substantially better levels of flexibility and economy.

The deregulation of Europe will promote longer point-to-point routes as barriers within Europe disappear after 1992. The similar needs for larger regional transports with speed and efficiency will prevail and also provide the best charter aircraft solutions for weekend traffic, when most regional equipment would go unused.

Regional transports tend to have a viable life of 15 years or more; hence, the next wave of major technical improvements in airframes is not expected until 2020, given that 2005 is when the introduction of new equipment is likely. VHB turbofan power will penetrate further down into the 30-passenger size as the cruise thrust-specific fuel consumption drops below 0.58 by the year 2015, but turboprops will remain dominant in the 19–40-passenger segment even beyond 2015, due to their lower cost of operation.

### **Short Takeoff and Landing and Vertical Takeoff and Landing Systems**

Shortened field lengths and high, hot-day performance for regional aircraft will set the requirements for short takeoff and landing (STOL) vehicles. The engine requirements for conventional and STOL aircraft will be similar, because STOL requirements will be met by high-lift wings and advanced thrust reversing systems.

### **Engine Requirements**

By 2000 there will be a need for a continuum of engines to support then-existing regional aircraft. This continuum includes turboshaft from 5,000–8,000 specific horsepower (shp), turbofans from 5,000–14,000 lbf thrust, and turboprops from 3,000–8,000 shp. Both conventional and STOL aircraft will be supported by the same engines since the STOL aircraft will utilize high-lift wings and advanced thrust reversing systems to reduce takeoff and landing distances.

As discussed earlier, the 35–60-passenger aircraft will be supported by either turboprop engines between 4,000 and 8,000 shp and high bypass/VHB ratio fan engines between 10,000 and 12,000 pounds. The gas generators or core engines of high-speed turboprops are very similar in size to those of regional jets, 7,500–9,200 shp. The fuel burn per hour of the turboprop is roughly the same as that of the regional jet, whereas the latter offers a 70–150-knot speed advantage along with a higher level of passenger comfort. Additionally, installed costs and weight of large turboprop engines are higher than for equivalent turbofan engines. However, existing engines (the 6,000–7,000 shp turboprop or 6,000–9,000 lbf thrust turbofan) are not designed with regional transportation in mind. These engines are simply available as a by-product of military or business jet applications. The next generation of advanced turboprops will need rugged cores optimized for regional aircraft.

The regional transport for more than 60 passengers will likely move toward higher bypass ratio turbofan engines to provide the best overall combination of fuel efficiency, high speed, low noise, lower emissions, and superior cabin comfort and ride. To drive the VHB turbofans and

provide low specific fuel consumption, overall compressor pressure ratios of 40–50:1 and turbine temperatures approaching 3000°F will be required.

The regional transport holding less than 35 passengers will continue to use turboprop engines. During the 1990s, the existing fleet will be replaced by a new generation of axial/centrifugal turboprops designed for the rigor of regional service and optimized for low-cost operations.

The key drivers for gas turbine propulsion technology for the short-haul transports are (1) cost, (2) range/fuel consumption, (3) reliability/dispatchability, (4) noise, and (5) emissions. These translate into engines with higher overall pressure ratio, increased turbine inlet temperature, higher bypass ratios, and low-cost, high-reliability controls and accessories.

### **Enabling Technologies**

Shown in Table 8-4 are state-of-the-art cycle parameters for axial centrifugal engines in these size classes and their future goals.

Other key technologies for short-haul aircraft propulsion systems are as follows:

- **Compressor:** Continuing to pursue high-compression systems will be key to reducing fuel consumption. By 2000, a combination of advanced three-dimensional CFD techniques and new material systems should allow 30:1 pressure ratios in three axial+centrifugal compressor cores.
- **Combustor/Turbine:** Improved combustor materials, fuel injection systems, and turbine materials will allow turbine inlet temperatures up to 3000°F. Coupling increased gas temperatures and advanced turbine work designs will further decrease the size and stage count of engine cores.
- **Controls and Accessories:** As turbofan engines are required to deliver more economical power, controls and accessories development will require increased emphasis. Controls and accessories are typically one-fourth to one-third the cost of the engine. By exploiting advanced computer and fiber-optic/signal concentration technology, the size, weight, and cost of these components can be reduced substantially.
- **Materials:** Key to most improvements in gas turbine performance and reliability are improved metallic materials and advanced intermetallics/nonmetallics. Advanced materials development includes titanium MMCs, titanium intermetallics, second- and third-generation single crystal alloys, and polymeric composites.

### **Observations for Short-Haul Aircraft**

The Committee believes that a strong, broad-based technology program is necessary to position the United States for the post-2000 short-haul markets. In general, NASA lacks awareness of the direction in which the short-haul/commuter market is heading and thus is not necessarily applying its resources appropriately. Currently, NASA seems to have much more interest in vertical takeoff and landing commuter systems than in conventional systems.

TABLE 8-4 Cycle Parameters for Axial Centrifugal Engines

Parameter	State of the Art	2000	2007	2015
Overall Pressure Ratio				
Turboshaft/prop	20:1	25:1	30:1	30-40:1
Turbofan	30:1	35:1	40:1	40-50:1
Turbine Inlet Temperature				
Turboshaft/prop	2400°F	2500°F	2600°F	2800°F
Turbofan	2250°F	2500°F	2800°F	3000°F
Specific Fuel Consumption				
Turboshaft/prop	Base	-7%	-16%	-20%
Turbofan	Base	-8%	-11%	-15%
Power- or Thrust-to-Weight				
Turboshaft/prop	Base	10%	16%	26%
Turbofan	Base	15%	35%	44%
Cost of Ownership				
Turboshaft/prop	Base	-5%	-10%	-20%
Turbofan	Base	-5%	-10%	-15%

The Committee believes that a better balance should be struck between the two. For example, a great deal of work has been done on large engines for subsonic aircraft. Some of this technology is applicable to the lower thrust and horsepower class of engines for the short-haul markets, but many areas that are unique to small engines deserve attention as well.

#### **Recommendations for Short-Haul Aircraft**

Cost of ownership and low initial purchase are key factors for the health of the short haul market. The Committee believes that NASA should undertake research activities that lead to lower-cost propulsion systems to benefit the general aviation and commuter markets.

The Committee also recommends that the LeRC direct its efforts at the "enabling technologies" discussed in earlier sections of this chapter and that NASA begin agency-wide

design efforts to identify configurations that are most suitable in the development of those technologies.

## HIGH-SPEED COMPUTATION FOR PROPULSION

The Committee believes that CFD and high-speed computation in general will be essential for new engine development in the coming decades, in order to shorten the time for development and to discover new design optima.

The government, including Congress, is strongly committed to enhancement of national computational capability through the High-Performance Computing Initiative (HPCI). The NASA-managed Numerical Aerodynamic Simulator (NAS) already provides a national aeronautical capability. However, it is not widely appreciated how formidable a challenge adapting computation to the needs of propulsion is. The complexity and range of important scales in a turbojet engine, for example, make it impossible to foresee achievement, in the next 30 years, of complete computational simulations of propulsion processes.

Therefore, for the foreseeable future in propulsion, both CFD and experiments will be needed to efficiently apply the results to meet design goals. Because no single group can accomplish this integration, a new spirit of cooperation is needed among industry, NASA, and universities, based on broadly shared perceptions of the capabilities and interests of each.

"Analysis codes" are necessary to provide the basic predictive ability, at the finest level of detail, for the physics and chemistry underlying propulsion. "Design codes" are the essential direct tools for engine development; they should embody the best capabilities of analysis codes but, because of their different purpose, be far faster, easier to apply, and therefore necessarily less comprehensive and precise. There is a crucial need, obviously, for the developers of analysis and design codes to work in harmony, across organizational lines. Experiments to elucidate physics, generate new ideas or understanding, and evaluate component performance must go hand in hand with code development; yet money, manpower, and time requirements increasingly hamper such initiatives.

Technical challenges for high-speed computation include

- multistage turbomachinery flow with mixing and shock losses;
- combustor design for low emissions, using codes that integrate chemical kinetics, fluid mechanics, heat transfer, materials, and structures;
- unsteady phenomena fully represented in codes pertaining to new ideas about the stability and control of propulsion systems; and
- acoustics and noise, which must—through CFD—be featured in the primary design process.



**Role of NASA**

The Committee believes that NASA, probably through LeRC, should be the nation's leader in the effort to meet computational needs such as those described in the previous section for propulsion.

- **NASA must be the advocate for the computational needs of the propulsion community; it must make sure that the HPCI supports propulsion and that the NAS capability is increasingly useful for propulsion research.**
- **NASA has a special responsibility to develop analysis codes of the greatest possible scientific scope and sophistication as resources for the propulsion engineering community, and to help the community appreciate and use these codes.**
- **NASA should perform the necessary experimental research to support and augment computational studies.**
- **Underlying all analysis and design codes are physical models of relevant phenomena; by means of appropriate experimentation, these models must be developed and improved, and NASA should lead this effort.**
- **NASA should use its computational capabilities to encourage and develop new propulsion ideas; these should aim for long-term advancements, looking far beyond the present needs of engine manufacturers. An appropriate degree of authoritative judgment and advocacy about the future should be provided by NASA.**
- **NASA should develop interdisciplinary technical communication pathways in the propulsion community.**

The Committee has found that management at LeRC is very alert to the above issues. Its technical program is well conceived and thoughtfully planned, especially when funding is generous, as in the case of high-speed research for HSCT. The limitations are chiefly traceable to inadequate support for generic research, including subsonic topics, and to difficulties in new staff recruitment.

The duty to lead in providing the propulsion community with access to advanced computational facilities is taken very seriously by LeRC. Access to the NAS is apparently satisfactory, and a push toward parallel processing capability is underway through an Advanced Computational Concepts Laboratory. LeRC, through its Numerical Propulsion System Simulator program, participates in HPCI. However, NASA advocacy of that role is not as strong or successful as it should be.

LeRC is very active in the development of CFD analysis codes for application to turbomachinery. However, the communication of NASA results to the propulsion industry is not always successful, so LeRC analysis codes are not always appropriate or easily adapted to industry needs. On the other hand, the working-level communication, leading to successful incorporation of LeRC algorithms, models, or subroutines into industrial design codes, is very

good. A better job clearly needs to be done in facilitating the cooperative development and use of NASA and industry codes, with the recognition that even the best analysis codes are not automatically applicable for timely design.

**NASA should lead in the development of innovative techniques of technical communication with industry in the general area of computational science as applied to propulsion.** Although NASA should take the initiative in this process, it is clearly necessary that industry management enthusiastically join in.

A particularly strong computational effort to analyze multistage machines, using an averaging hierarchy, is unique to LeRC and may well provide important insights for the next generation of advanced subsonic engine designs. The HSCT interest is sustaining code development for predicting unsteady engine performance. CFD with chemical kinetics is a LeRC capability that may soon be joined with the experimental studies of low-NO<sub>x</sub> combustors at LeRC; this development follows from the HSCT initiative but will surely benefit subsonic engine development in the next decades.

The HSCT program also supports a program of computational acoustics in the Langley acoustics division, in cooperation with engine studies at LeRC. At LeRC, prospects for developing a first-principle solver for jet noise are being pursued energetically. The Committee hopes that this program will have support commensurate with the enormous practical importance of propulsion noise, not just for HSCT but for subsonic developments as well.

Serious efforts are being made to integrate experiments with code development, especially by exploiting laser-Doppler velocimeter (LDV) techniques. The Committee heard comments that LeRC was not providing the experimental component research data that were such valuable NASA (and National Advisory Committee on Aeronautics) contributions in the past. Although funding and staffing reasons for this will remain, it does seem that LeRC is moving toward meeting this need in tandem with code development. In the recent past, criticisms could be made that experimental component studies were abandoned in favor of CFD and that surviving experiments were to be driven only by "code validation." A much more sophisticated view now prevails, which encourages experimental and computational teamwork. The difficulties of such teamwork—especially time and funding on the experimental side—are severe, but one can hope for a trend toward more "component research" of significance in the next decade.

An interesting example of experimental-computational teamwork in furtherance of a new development having system and component consequences is the Supersonic Through-Flow Fan program at LeRC. This program depends on CFD for the next steps in which refinements and modifications will look toward engine application. Equally, the experimental program will have to be extended. A challenge will be to keep experimental time requirements in bounds; no doubt increased professional staff is the chief requirement for timely progress.

The Numerical Propulsion System Simulator (NPSS) is intended, in the very long run, to provide a uniformly valid numerical simulator for propulsion systems, by taking into account all relevant fluid and structural issues. This is certainly an appropriate long-range goal for NASA. The path toward that goal involves the generation of numerical analysis tools, in cooperation with an industry steering group that provides current thinking about engineering design goals. The models on which the developing code structure is to be based themselves

require continuous development so that the various codes can interact at consistent levels of validity. This process can clearly have great power to discipline the entire LeRC propulsion program and to ensure centrality to the national propulsion development effort.

At present, an enthusiastic industry team is in place, and certain component analysis tasks have been identified for intensive study (e.g., a fan-nacelle system). An obvious future need is to develop acoustics codes of the right level to be included in this general scheme. Industry participation is at working level, which is good because this is a program that synthesizes technical information about components. On the other hand, the Committee found that management in both industry and NASA does not have a very vivid picture of this program.

Although a full-blown "numerical test cell" is not likely for the time frame of this study, significant progress in unifying numerical propulsion analysis techniques could certainly be made. Therefore, the Committee would like to see a stronger management response to this significant grass roots initiative from all quarters, a response that recognizes the potential importance of NPSS for the future of both LeRC and the propulsion industry.

## **MATERIALS AND PROCESSING**

Both advanced subsonic transports and the HSCT require materials that exhibit drastic improvements in strength-to-weight characteristics, fatigue life, and high-temperature capability. Many of their applications will necessitate unique procedures to fabricate and repair radically different components. Innovative manufacturing methods must be developed to fabricate components from these advanced materials at affordable costs.

### **Drivers for Materials Development and Requirements for Application**

Drivers for materials development for either the HSCT or the Integrated High Performance Turbine Engine Technology program are (1) specific strength, (2) specific stiffness, (3) damage tolerance, (4) special physical properties, (5) producibility/reproducibility, (6) maintainability/repairability, (7) temperature capability (creep and environmental survivability), and (8) cost: raw materials, fabricability, shop handling.

Specific advanced composite systems needed for advanced engines are shown in Table 8-5, along with propulsion applications for the HSCT and the advanced subsonic transport.

Before any design incorporation and application can be considered, there must be adequate demonstration of both materials and processing technology readiness to support the confidence to launch full-scale engine development. The following are key requirements for this confidence:

- sufficient property characterization for design and determination of life cycle costs;
- established design methodology, including life prediction systems;
- reproducible manufacturing processes;
- demonstrated repairability/maintainability;

TABLE 8-5 Potential Applications for Advanced Composites

Composite	Application
Polymer matrix composites	Ducts, cases, and structure
Metal matrix composites	Reinforced rims on high-speed turbine and compressor disks or drum rotors, stators and cases, fan blades
Intermetallic matrix composites	Lightweight, low-noise exhaust nozzle, low pressure turbine rotors
Ceramic matrix composites	Low-NO <sub>x</sub> , high-efficiency combustor; high pressure turbine disk hoop reinforcement; exhaust cases

- validated technology (by engine test);
- realistic, substantiated cost estimates for production; and
- realistic assessment of risk.

### **Special Economic Problems in Materials**

Compared with common materials, aircraft engine materials are generally more expensive and produced in smaller quantities. Even for current-technology engine materials (e.g., titanium) the number of suppliers is limited, and some parts (e.g., ball bearings) are mostly manufactured abroad. Many of the raw materials for the advanced composites listed in Table 8-5 are of the specialty type and of very high value. For some high-temperature applications, the raw materials cost \$4,000 to \$5,000 per pound, based on individual costs of \$2,000 per pound for fiber and \$2,000 to \$3,000 per pound for matrix. These materials are definitely not commodities, and producers have little interest in manufacturing either existing or new fibers in small quantities. Such materials have a poorly defined market potential because they have an uncertain breadth of applications and a market whose duration and extent are unknown. The result is commercial unavailability. The need is for an effort similar to that undertaken by the USAF in the 1950s to secure titanium as a producible engine material.

### **Manufacturing Issues**

Continued development of gas turbine engines in the next century will depend on two key factors: the ability to manufacture high-performance propulsion systems at affordable costs and the economical exploitation of advanced materials. Affordability is the major goal of

manufacturing technology. To ensure economical manufacture of advanced components from new and current materials, new processing methodologies and enterprise systems must evolve into reliable production techniques. Speed, with quality, must be the primary focus of the product development cycle, and the production process must be shortened drastically. Quality enhances affordability; intelligent systems that manufacture parts with no variability will significantly reduce the cost of those parts.

The maturation of intelligent processing will depend on the successful development of full adaptive control; process modeling and verification, insitu measurement with advanced sensors, and integration of all adaptive control systems. Process understanding must be great enough that processing trends can be detected and corrections made in real time. Precision manufacturing is part of the intelligent processing approach. The intelligent machine must know in advance that it will produce a quality part; hence, tailgate inspection may be eliminated and on-machine inspection minimized. Through precision manufacturing the factory of 2010 will be able to make products with improved performance at lower cost because part variability will be eliminated.

Emerging enterprise systems must be integrated with advanced processes to increase productivity and reduce processing time at the machine tool level, cell level, and factory floor level. Machine tools, for all types of processes, must be self-contained, intelligent processing systems—self-directed, self-monitoring, and fully adaptive, with automatic tooling setup capability. The cell must have the ability to operate as an intelligent business unit capable of precision-manufacturing small lots of parts. Control at the floor level must include the capability to synchronize the operation of all cells and machine tools to provide the necessary components, on time, for final engine assembly. The ability to manage information flow will be critical. The overall system must integrate the performance of the suppliers to ensure timely delivery of all manufactured parts.

Evolution of the optimum manufacturing enterprise will require advancements in four areas: skilled personnel, intelligent computer systems, automated manufacturing equipment, and precision manufacturing processes with full adaptive control. The factory of 2010 will require fewer but more highly skilled people. Optimization will be emphasized from the entire factory perspective. Standardization, as the precursor to integration, will be the focus of computer-integrated manufacturing (CIM) as computer power continues to grow. The machine tool, for all processes, including those that are nontraditional, must be a fully automated, intelligent device. It must have the ability to run continuously with no human intervention; it must be flexible, with adaptive tooling/fixtures and intelligent software that controls maintenance and tool design; and it must have the necessary sensors integrated for full adaptive control. CIM technologies must also enhance responsiveness and reduce the product development cycle. Systems must be put in place to create functional prototype parts on demand.

### **Role of NASA in Materials and Manufacturing**

**NASA should continue its major role in materials research and development and extend it into the area of materials processing.** Historically, NASA has limited its involvement in manufacturing technology, based on the assumption that the Department of Defense (DoD) and industry were best able to accomplish this task. Only in certain large NASA projects were materials disciplines incorporated with some form of manufacturing technology to accomplish the project goals. These include the Energy Efficient Engine program, the Engine Component Improvement program, the Composite Primary Aircraft Structures program, the Materials for Advanced Technology Engine program, and the Advanced Composites Technology program. NASA contributed only indirectly to the needs of the manufacturing community.

However, the invention of a new laboratory material and its characterization in laboratories do not guarantee useful innovation. Incorporation of a new material in an engine spans 10–20 years, much of the which is occupied with the process development necessary for continuous, reliable production. **NASA's responsibility for materials research and development should be extended into the realm of materials manufacturing to incorporate process development cooperatively with engine producers and materials producers. NASA should ensure validation for full-scale producibility of new materials.**

As NASA reexamines its role in support of manufacturing, it should avoid a program modeled on the DoD/USAF MANTECH program. First, NASA is not a large procurement agency for current aircraft engine parts. Second, the MANTECH program is relatively short-term with a required implementation plan that includes a cost/benefit analysis showing how the supported effort will be of near-term benefit to the company. Rather, if NASA is to assume a greater role in manufacturing research and development, it should be in longer term, higher risk, more fundamental technologies for which the immediate payoff is not obvious.

One possible area, suggested by the industry, for NASA to examine is the application of its analytical expertise to the physics and mechanics of particular manufacturing processes, materials characterization, and modeling, as well as intelligent process control research, employing real-time sensors and embedded process models. NASA, industry, and the universities should all be involved. Care must be exercised that the subjects chosen are real, long range, and not parochial in nature. **It is essential, however, that this work be undertaken with an increased budget, not through reduction of existing useful programs that NASA is now funding.**

### **Recommendations for Propulsion Materials**

**In the opinion of the Committee, NASA should**

- **continue in its historic role of materials research and development for propulsion applications;**

- extend its materials research and development programs into the realm of manufacturing to incorporate process development, in cooperation with engine materials producers, to ensure validation for full-scale production;
- examine and provide solutions, in the form of program support, for the development of specialty materials that are not available as commodities but, if properly supported and developed, will become common in aircraft engines; and
- reexamine its general historic role in manufacturing and assess its ability to fund fundamental projects of a long-term, high-risk nature, involving industry and universities, in analyzing the physics and mechanics of particular manufacturing processes, materials characterization, and modeling.

## SMART ENGINES

The explosive growth of computer technology, fostered by the microelectronics revolution, is a strong driver for change in aeronautics, from avionics in the air to air traffic control on the ground. The air vehicles themselves have been evolving rapidly as the capability, functionality, and complexity of airborne electronics grow. Full-authority electronic digital controls are now routine on new commercial and military engines. With this resultant increase in computational power, the nature of engine control is moving away from the engine governor toward improved functionality and integration with aircraft flight controls. These are evolutionary changes, however, using processors common to personal computers.

Over the past five years, a number of researchers have been investigating the use of active controls applied to the component or subcomponent (compressor, burner, bearings, structure, etc.) level in gas turbines. This work has introduced the concept of a smart engine requiring several orders of magnitude more computational power than current advanced designs. This revolutionary approach incorporates feedback control within the device that can alter both its static and its dynamic behavior, so that the performance of the component can no longer be extrapolated from the data base generated by years of experience. The impact of active components can come from improved component performance and also from a relaxation of conventional engineering constraints, thus enabling new solutions and new designs.

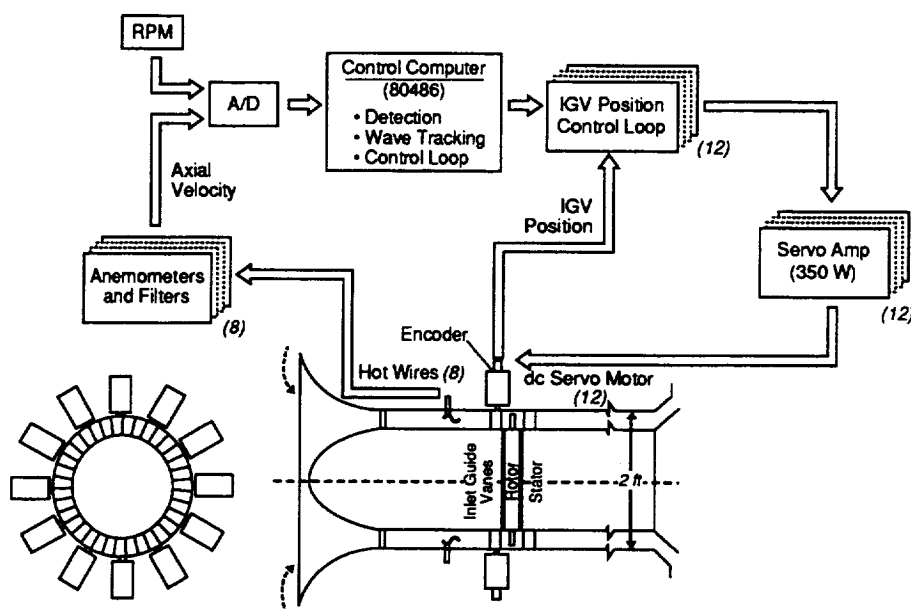
Active monitoring and control technology employed at the component level can be applied across the engine. Some areas of progress that are currently under investigation include

- active suppression of fan and compressor surge and stall,
- active combustor monitoring and control,
- magnetic bearings, and
- active noise controls.

The common theme of these areas is that they represent a radically new approach to problems that seriously limit propulsion technology. The technologies, however, differ in phenomenology and engineering approach.

### Active Fan and Compressor Stabilization

One of the most troublesome phenomena in jet engine design and operation is compressor surge and stall. These are large-scale oscillations in air flow that result in abrupt thrust loss and can inflict severe mechanical damage. Current practice is to detune the compressor by 20–25 percent (with concomitant loss of performance) to avoid operating in regions where instabilities occur. Surge and stall also place significant restrictions on inlet design because distorted air flow from the inlets can trigger fan and compressor instabilities.

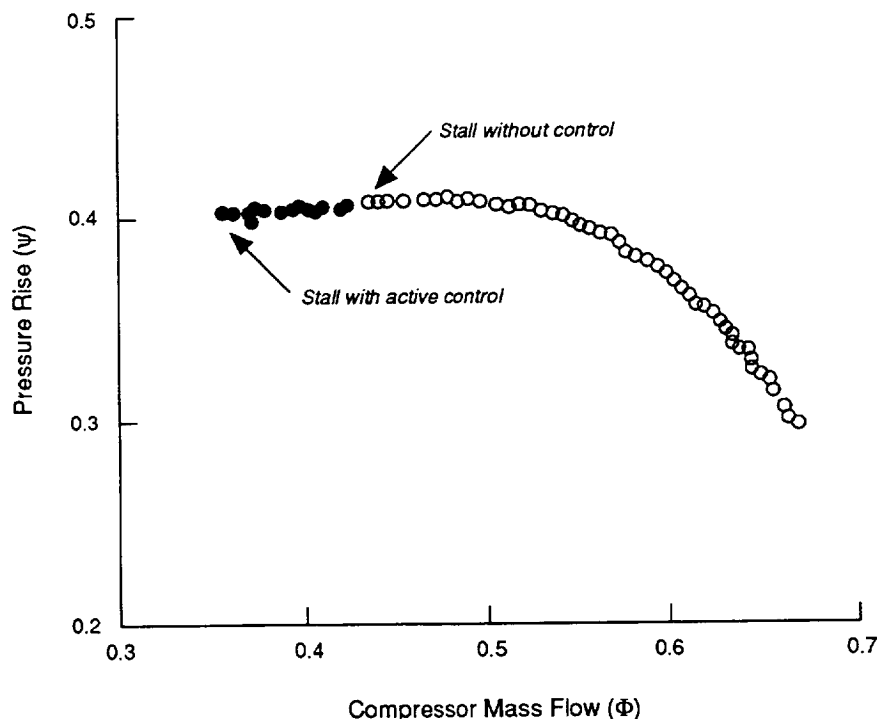


Source: Massachusetts Institute of Technology

FIGURE 8-4 Actively stabilized compressor suppresses rotating stall.

In the past two years, laboratory-scale experiments have shown that it is physically possible to actively damp a compressor by using feedback control. The concept is to sense the disturbances when they are small and launch counterdisturbances to damp them. The power required to do this is typically  $10^{-5}$ – $10^{-6}$  of the compressor power. One such implementation, for the control of rotating stall in an axial compressor, is illustrated in Figure 8-4. Here, a circumferential array of transducers is used to detect small-amplitude traveling waves, which are damped by wiggling the compressor inlet guide vanes to launch counterwaves. Decreases in the stalling mass flow of up to 25 percent have been demonstrated in this manner (see Figure 8-5).





Source: Massachusetts Institute of Technology

FIGURE 8-5 Active compressor stabilization moves the stall point to lower mass flows.

Similar gains have been shown for the control of surge.

There are significant potential advantages to stabilizing the fan and compressor against rotating stall and surge, including (1) lighter fan compressors (fewer stages and shorter chord airfoils), (2) improved compressor efficiency (more freedom in component matching), (3) increased distortion tolerance (shorter inlets, reaction control system considerations), (4) improved inlet-engine matching (reduced spillage drag), and (5) increased compressor design freedom. If the demonstrated gains are realizable in full-scale engines, system study has shown there can be dramatic improvement in aircraft performance or weight.

### Active Combustor Control

Combustors also suffer from instabilities, especially in afterburners and ramjets. Active control of these instabilities has yielded both a 15-dB reduction in rumble instabilities in afterburner geometries and more complete combustion, permitting high power levels and shorter combustors.

Active control has also been demonstrated in can-type geometries of main gas turbine combustors. Here, low-amplitude acoustic waves have been used to decrease the pattern factor

(homogenize the flow) by 50 percent, potentially improving turbine durability and life. Active control may be necessary for lean-burn, ultralow-emission main burners for advanced subsonic and HSCT aircraft.

### **Magnetic Bearings**

Magnetic bearings suspend the rotating members in magnetic fields, eliminating friction and lubrication requirements. Specific advantages over rolling contact bearings include elimination of the lubrication system, active damping of shaft dynamics and vibration, greatly increased temperature capability (up to 800°C), and large increases of load capability (two to four times).

Magnetic bearings using conventional electromagnets are currently employed in large ground-based turbomachinery. Improved designs are capable of supporting typical gas turbine loads using less than 100 W. Since bearings of this type are inherently unstable, active control is required to maintain position. Active control enables the dynamics of the system to be optimized in software, greatly increasing design freedom and vibration damping. Current estimates are that an engine with magnetic bearings could have a 5 percent advantage in weight and a 5 percent advantage in efficiency over a conventional design.

### **Active Noise Control**

Feedback control can be used to reduce noise either by direct wave cancellation or by influencing the noise-producing phenomena. Exhaust noise reductions of more than 20 dB have been demonstrated on large-scale ground-based gas turbines. Although perhaps further from practical aircraft realization than other smart engine technologies, active noise control offers the promise of a new approach to one of the most vexing of problems facing aviation, especially the HSCT.

### **Recommendations for Smart Engines**

Should the results of these small-scale experiments extrapolate to full-scale engines, active control has the potential to improve aircraft propulsion performance and design in important ways. There is a long way, however, between small experiments and full-scale engine development. These are high-risk, high-reward technologies, with application unlikely before the turn of the century. As such, most of these concepts are beyond the horizon that U.S. industry is prepared to pursue.

**The Committee believes that NASA is uniquely positioned to pursue active control technologies for aircraft engines. NASA has both the personnel and the facilities to bring the technology along from university benches to the large-scale experiments necessary to assess concept viability prior to development by industry. NASA also has the breadth of disciplines at its centers and among its contractors to forge the teams (e.g., fluid mechanics, controls, structures) necessary to successfully pursue smart engine technology.**

## TURBOMACHINERY COMPONENT TECHNOLOGY

Significant advancements in the design methodology of turbomachines are needed to satisfy the requirements of both the advanced subsonic transport aircraft and the HSCT. Turbomachines for these systems should have fewer airfoils, reduced gaps between airfoil rows, lower aspect ratios, and higher clearance-to-span ratios. These machines must operate at high Mach numbers and lower Reynolds numbers, the latter in low-pressure turbines. The cooling air and turbine inlet temperatures are expected to be higher, whereas the amount of cooling and secondary air will decrease. The necessary solutions for these problems will emerge from the challenging fundamental research and development activity of the next 10–15 years. Continued advancements in CFD, together with improved flow measurement techniques, show the promise of utilizing more reliable analytical methods. However, the availability of advanced computational and experimental methods for turbomachinery design does not, in itself, ensure a more efficient and durable machine. The design process also relies very heavily on experience-based correlations and turbulence models and on design criteria. Implementation of advanced CFD codes without improvements in design criteria may not yield an improved design. The complexity of turbomachinery flows requires a national program to develop design systems for the next generation of gas turbine engines.

### Fluid Mechanics of Turbomachine Elements

Among the issues facing turbine and compressor designers are the following:

- Two-dimensional airfoil optimization: Significant reductions in airfoil losses have been achieved over the past 15 years through the control of boundary layers, specifically by designing laminar flow and controlled diffusion airfoils. In current turbomachines, losses generated on airfoil surfaces constitute between 30 and 60 percent of total losses. Substantial increases in losses are measured for airfoils operating at transonic Mach numbers. Currently, low-loss airfoils in the transonic flow regime are designed by using simple criteria along with extensive experimental data. In the future, accurate numerical calculations from two-dimensional Reynolds-averaged Navier-Stokes codes can be used together with controlled experiments in plane cascades to develop design criteria for transonic flow applications. The guidelines needed to design low-loss airfoils for low Reynolds number application can be developed by using direct numerical simulation to identify transition criteria in separation bubbles.
- Endwall losses: The endwall regions contain 20–30 percent of the total losses in turbomachines. The physical mechanisms governing these losses are not well understood, and their magnitudes are 1.5–7 times larger than those estimated on the basis of wetted-surface calculations. There is a need to conduct accurate numerical simulations to identify loss generation mechanisms in the endwall region and to identify design criteria to develop low endwall loss passages.

- Tip clearance loss control: Tip leakage flows are responsible for 10–40 percent of the total losses in turbomachines. Although flows in the tip clearance regions are highly complex, the loss in efficiency due to tip clearance is linearly related to the fractional clearance. There is a potential to control tip clearance flows by designing airfoils to limit the amount of flow in the tip regions. Numerical simulations can play a very important role in this area if they are verified through experimental programs.
- Heat loads on airfoil pressure sides: Measured heat loads on the pressure sides of rotor airfoils are two to three times larger than those calculated by using current prediction methods. Since the amount of cooling air for rotor airfoils is controlled primarily by pressure-side heat loads, there is a need to develop reliable prediction methods to estimate them. Low heat load design concepts can potentially reduce cooling air requirements.
- Shock boundary layer/vortex interaction: Significant losses are generated from the interaction of shocks with boundary layers, and with tip leakage vortices. Shocks in fans cause the separation of boundary layers, which provides a conduit for the low-momentum flow to migrate toward the tip region. Shocks also interact with tip leakage vortices; this interaction can initiate stall in the rotor. Accurate numerical simulations must be conducted to identify the detrimental effect of shock interaction. There is also a need to develop turbulence models to provide accurate estimates of shock-induced losses on airfoil surfaces. Both numerical and experimental programs are required to develop flow prediction methods for high Mach number applications.

### Problems of Multistage Turbomachines

Turbomachine flows are highly unsteady due to the relative motion of adjacent airfoil rows and incoming total pressure and total temperature profiles. Steady flow simulation methods, which have historically been used, fail to account for three specific flow features: (1) preferential migration of wakes from upstream airfoil rows; (2) preferential migration of hot and cold streaks toward the pressure and suction sides, respectively, of turbine rotors; and (3) preferential migration of endwall secondary flow and tip leakage vortices from the upstream airfoil row to the downstream airfoil passages, causing substantial effects on heat loads and losses. The effects of these flow phenomena are currently accounted for by using empirical correlations that are not very well grounded in flow physics. This situation will be further aggravated by current design trends. Available empirical correlations will not provide realistic flow behavior in the multistage turbomachines. Work needs to be initiated to develop physically sound models that account for the effects of periodic unsteadiness in multistage turbomachines. A promising multistage flow simulation strategy has been developed at LeRC, and concerted effort should be directed toward further development of this approach.

### **Combined Computational Fluid Dynamics for Airfoil Rows**

Flow leakage from endwalls is expected to increase in future turbomachines. CFD codes, therefore, need to be developed and validated in order to provide accurate flow simulations for airfoil flow passages that have significant amounts of secondary air leakage. Prediction methods also need to be developed for airfoil rows having a significant amount of cooling air injection from airfoil and endwall surfaces. A rational approach is to develop a procedure that will compute flow through the internal passages of the turbine, a heat conduction code, and a solver for the airfoil passage. Such an approach is likely to provide a more accurate and faster method for predicting both performance and surface temperature for airfoil rows.

### **Observations on NASA Turbomachinery Program**

The turbomachinery technology program at LeRC is extensive and contains some very significant and important elements, but, due largely to lack of funds and personnel, the pace of the work may be too slow to maintain the excitement it merits. It appears that the amount of innovative component research there is substantially less than it was two decades ago, when NASA contributed heavily in ideas and experimental results that led to strong advances in the industry. There are, however, excellent areas of work, of which three are mentioned below:

- **Supersonic through-flow fan:** This is a fine example of innovative technology firmly grounded in fundamental fluid mechanics, with the promise of significant performance gains in engines for supersonic flight. The design of the fan and the structuring of the experimental program have made effective use of the LeRC CFD capability, and its successful operation lends credibility to both the concept and the design method. Again, the pace of the work is slower than desirable or appropriate for a project carrying such promise. Essential work remains to be done in the design of the stator, improvement of the stage performance, and the mechanism of starting.
- **Cooperative compressor research with Allison:** LeRC has undertaken a cooperative research program with Allison on an advanced two-stage compressor with a pressure ratio better than 5:1, handling a through-flow of about 10 pounds per second. This is a high-performance compressor that is a very aggressive design and situates LeRC at the leading edge of compressor technology.
- **Multistage turbomachine flow computation and design:** This effort at LeRC is a highly innovative computational scheme realistic treatment of the fundamentally unsteady flow in multistage turbomachines. It represents an excellent example of scientific engineering, having its foundation in fundamentals while aiming at meaningful approximate calculations for design purposes. The technique recognizes the presence of fluctuations in the frequency range of blade passing and separately in the range of rotative speed, and works with relatively independent time averages in these ranges. To fulfill its promise, method

requires experiments and computations focused on the determination of some of these average quantities; these are evidently not being pursued at present.

These very promising activities suggest that increasing their number and augmenting their support merit serious consideration.

### **Recommendations for Turbomachinery**

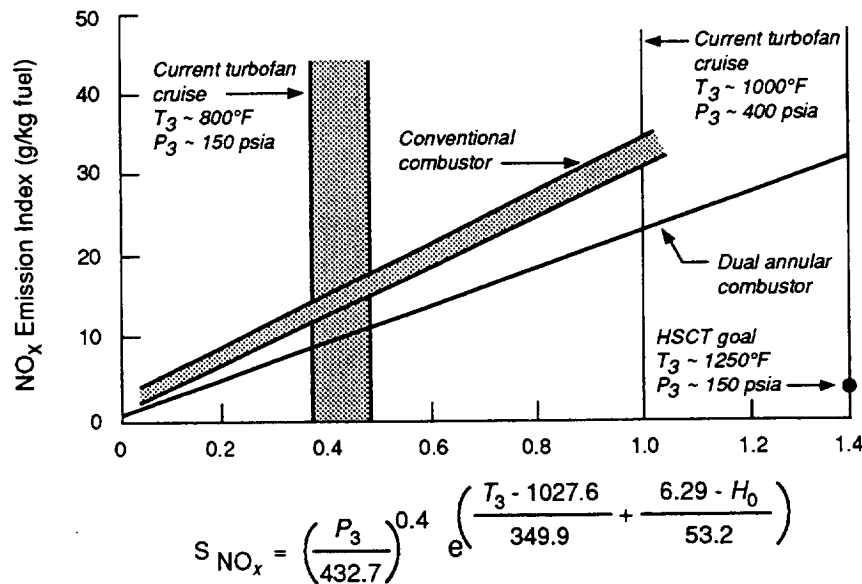
It has been the historic role of NASA, and one that industry has found beneficial, to provide a focus for research activity, to undertake innovative component experimental research, and to give leadership to teams consisting of industry, university, and government agencies. The current environment requires, in addition, that NASA assist in providing computer resources for numerical simulation and that it cooperate in the development and standardization of various CFD codes to facilitate evaluation against basic data and permit ready incorporation into design codes.

NASA has been slow to respond to the exciting potential of stall and surge control and has not yet taken steps toward development of sensors and actuators required for its implementation. Although the capability of such control has been unequivocally demonstrated, the development of techniques appropriate to operational engines demands a strong and innovative effort. Another area in which additional effort would be welcome is the problem of short blades that will be encountered in latter stages of new, very high pressure ratio core engines. NASA's work on the off-axis independent compressor is very promising but should not constitute its total effort in this area.

### **COMBUSTORS AND EMISSIONS**

Although the emission of nitrogen oxides, carbon monoxide, and unburned hydrocarbons constitutes a significant issue for subsonic commercial transports, and promises to become a larger problem for short-haul aircraft as this traffic increases, the currently intense interest centers on the HSCT. Here, the  $\text{NO}_x$  emissions are a central issue for flight in the stratosphere, where particulate exhaust and the formation of ice crystals together with the oxides of nitrogen constitute a potential threat to the ozone layer. The development and design issues, which are already sufficiently complex, are further clouded by currently inadequate, but slowly evolving, models of the upper atmosphere that will play a role in setting standards for altitude exhaust emissions. Moreover, it is not clear at present just how a known body of engine exhaust information would be coupled meaningfully to the grid of atmospheric models now in use.

Engines for current subsonic transport aircraft emit between 10 and 20 g of nitrogen oxides per kilogram of fuel (see Figure 8-6), depending on whether the combustors are of the conventional design or the more recent dual annular design. Under takeoff conditions, emissions from these same combustors increase to between 20 and 30 g/kg fuel. If this performance is scaled on the basis of the nitrogen oxide "severity index" currently employed, the HSCT would be expected to produce between 30 and 40 g/kg fuel at cruise conditions. The goal for HSCT



Source: National Aeronautics and Space Administration

FIGURE 8-6 Nitric oxide emissions versus severity index(s), current and future engines.

engines is 5 g/kg fuel—between 12 and 16 percent that of current engines—the requirement could be set even lower, more out of uncertainty than rationality.

Clearly this reduction by a factor of six or more requires heroic measures. Recognizing these facts in the early 1970s, LeRC embarked on a low-emissions burner program that focused on what became known as the lean premixed prevaporized burner. Subsequently, this effort led to NASA sponsorship of separate research and development programs with P&W and GE. Two candidate burner technologies were identified and these continue to be pursued by the two engine manufacturers. Research on the chemistry and gas dynamics of  $NO_x$  reduction continues at LeRC.

The production of nitrogen oxides increases with pressure, temperature, and residence time in the combustor. Consequently, reduction techniques focus on just what latitude one has with these variables in view of the engine cycle requirements. Not only is temperature the most sensitive of these, but owing to the design of conventional burners, it also offers the greatest possibility for control. In the conventional engine, fuel is initially burned at approximately stoichiometric conditions and subsequently diluted to the desired leaner condition. The high temperatures in the primary combustion zone result in rapid production of  $NO_x$  during its residence time and set the value of the final emission level. The advantages of this arrangement are that the hot, stoichiometric primary zone provides good stability, ignition, and relight, while the addition of dilution air allows convenient cooling of the combustor liner. The low- $NO_x$  burners are consequently designed to avoid the hot stoichiometric and dilution zones, thereby reducing emissions, but at the expense of stability and cooling problems.

The  $\text{NO}_x$  formation rate shows a strong dependence on mixture ratio, as a result of the dependence of temperature on mixture ratio. In a conventional burner the primary region produces  $\text{NO}_x$  at nearly the peak value, and subsequent air dilution decreases the production rate to less than 1 percent peak value at combustion discharge conditions. The lean premixed, prevaporized concept reverses the procedure by preparing the fuel/air mixture at its desired final value and carrying out the combustion at a very low  $\text{NO}_x$  production rate. The near symmetry of the  $\text{NO}_x$  production rate about the stoichiometric mixture suggests the alternative procedure of burning with a rich mixture and subsequently diluting it rapidly to the desired final lean condition. This technique underlies the second type of low- $\text{NO}_x$  burner under serious consideration.

A combustor that introduces a lean, premixed, prevaporized mixture into the combustion chamber is being pursued by GE. With this design it is necessary to mix the air and the fuel vapor thoroughly on the molecular scale to achieve the indicated reduction of nitrogen oxides. Moreover, because this mixture volume constitutes a source of preignition and flame flashback problems, the mixing must be very rapid to minimize the mixture volume and residence time. To accommodate the anticipated range of operating conditions, variable-geometry vapor inlet and bypass air controls are required as well as the corresponding sensors. Furthermore, because the larger part of the air is mixed before combustion is carried out, the dilution air conventionally available for combustor liner cooling is much less accessible. As a consequence, high-temperature materials are essential.

The second option, that of rich burning, is being pursued by P&W and, for reasons that will become obvious, has been designated the Rich Burn Quick Quench burner. In this burner the fuel and a limited amount of air are introduced into the rich stage. Here again, it is absolutely essential that the fuel-air mixing be carried out on a molecular scale before combustion occurs. To the extent that mixing is nonuniform, the reaction will preferentially take place in those regions where the mixture is close to stoichiometric, thus partially defeating the aim of the burner. As dilution air is added, each portion of the mixture passes through the stoichiometric ratio and will produce nitrogen oxides at that very rapid rate. Consequently, rapid mixing during the quench phase is essential. Again, because the temperatures are higher than conventional and because bleed liner cooling is unacceptable in the rich burn stage, high-temperature materials are essential.

These ultralow- $\text{NO}_x$  burners entail higher than conventional pressure losses due to the requirement for rapid mixing, the use of new high-temperature materials, variable geometry, and the attendant controls and sensors. In addition, it appears that these burners may be somewhat longer than conventional and entail an increased engine weight that is, as yet, undetermined.

The cooperative development of the HSCT engine, between P&W and GE, permits efficient and economical exploration of these two burner types; it is essential that NASA, P&W, and GE get their Joint Technology Acquisition Program in place. In addition, it is of the utmost importance that LeRC continue vigorously its basic research in this area, driving toward  $\text{NO}_x$  levels even lower than the present goal of 5g/kg fuel.

Airport  $\text{NO}_x$  emissions will be a challenge for the advanced subsonic engine cycles with 70:1 pressure ratio and 3000°F turbine inlet temperature. With current combustor types, the



NO<sub>x</sub> per unit of thrust could be tripled under these conditions. A good target would be to decrease NO<sub>x</sub> emission to an absolute level half that of current engines. This will require very advanced combustors employing variable geometry, new materials, and smart controls.



## MATERIALS AND STRUCTURES

### INTRODUCTION

At various stages in the evolution of aeronautics, one of the foundation disciplines—aerodynamics, propulsion, control, or structures—has been either the obstacle to progress or the conduit to major improvements. They all, therefore, constitute "enabling technologies." In the sense, however, that no airfoil will develop full lift if its surface cannot maintain shape and smoothness under the pressures it is designed to generate; that no engine will function if its components cannot withstand fuel combustion temperatures and rotation loads; and that no control system can cause aircraft attitude changes if its linkages will not carry the forces that create hinge moments—in that sense, structures and the materials used to build them are first among the enabling, foundation aeronautical technologies. Providing a safe and durable structure is a matter of fundamental importance, because a functional failure of structural components usually has catastrophic results. This chapter discusses the committee's findings and recommendations regarding future materials and structures technology. The boxed material summarizes the primary recommendations that appear throughout the chapter, with specific recommendations given in order of priority, and the benefits that can be gained through research and technology development efforts aimed at advanced structures and materials.

Beyond being an enabling technology, development of the structures of airframes and engines continues to be a key element in determining the economic success of aircraft. Structural weight is the single largest item in the empty weight of an aircraft and is, therefore, a major factor in the original acquisition and operating cost and in establishing operational performance. One pound added to structural weight requires additional wing area to lift it (all other flight variables being held constant), additional thrust to overcome the associated incremental drag, and additional fuel to provide the same range. All these additions result in further increases in structure. This vicious circle converges, in typical aircraft designs, to gross weight increases from 2 to 10 times the 1-pound empty weight increase that began the cycle.

The trend in aeronautical structures from all-metal construction to composite airframes, which began about 25 years ago, has reached the point at which specialized military aircraft, fighters, and vertical takeoff and landing (VTOL) aircraft, now have composite structures

### Recommendations

#### General

NASA's structures and materials program should emphasize continuing fundamental research to achieve both evolutionary and revolutionary advances in materials and structures, as well as focused technology programs in materials and structures to address specific aircraft system requirements. This should include:

- a major role in establishing the data base that is required for realistic materials- and structures-related regulations;
- a significant increase in NASA's investment in the technology of shaping, forming, and fastening; and
- a lead role in stimulating innovative structural design and manufacturing research for both airframes and engines in a program conducted jointly with industry.

#### Specific

1. The highest priority in NASA's long-range engine materials research program should be on ceramic matrix composite developments including fabrication technology, although intermetallics should continue to be an active part of engine materials research for the longer term, with emphasis on improving damage tolerance.
2. NASA's program of basic research in materials and structures should improve understanding of failure modes in composites, increase damage tolerance, and introduce advanced means of nondestructive evaluation.
3. Automated sensing and feedback control should be an increasing part of NASA's research program, capitalizing on "smart structures" advances.
4. The introduction of metal matrix composites into high-pressure compressor disks deserves major emphasis in NASA's engine programs for the nearer term.
5. NASA's program of materials and structures research for the HSCT should give high priority to developing basic composite materials, advanced metallic systems, and design concepts and processing techniques for 225-375°F operations.

constituting from 40 to 60 percent of the airframe weight (AV-8B and V-22, respectively.) Commercial transports use advanced composites in essential secondary structures such as flaps and control surfaces and in some primary structure such as vertical fins.

The advantages of composite materials, as exemplified by their greater strength and stiffness per unit weight, superior fatigue and corrosion resistance for many applications, and potential for lower manufacturing costs through reduced part counts and tooling expenses, make their wide application to U.S. aircraft designs a compelling need. However, the slow rate at which they are being adopted is evidence that their design, analysis, manufacturing, inspection, and repair methodologies are all in a developing state.

**Benefits of Research and Technology Development in Structures and Materials****Aircraft Operations**

- Reduced cost
  - Reduced airframe and engine weight
  - Reduced maintenance requirements
  - Long-life materials
  - Design for maintenance
- Enhanced safety
  - Predictable material fatigue
  - "Smart structures"

**Aircraft and Engine Design and Development**

- Shortened development cycle
  - Improved computational capabilities for materials and structures
  - Improved testing facilities for materials and structures
- Technology validation

Aircraft structural design, analysis, manufacturing and validation testing tasks have become more complex, regardless of the materials used, as knowledge is gained in the flight sciences, the variety of material forms and manufacturing processes is expanded, and aircraft performance requirements are increased. A greatly expanded design data base of applied loads is now available for more complete and thorough definition of critical design conditions, thanks to the expanding use of computational fluid dynamics (CFD), advanced wind tunnel testing techniques, and increasingly comprehensive aeroelastic and structural dynamic analysis computer codes. Similarly, computer-aided design tools make it easier and quicker to consider a much greater variety of alternative structural designs. The use of high-speed, large-memory computers permits, in turn, more detailed internal structural loads analysis for each of the many loading conditions and design alternatives, with fine grid analysis determining more precise load paths, stress distributions, and load deflection characteristics for subsequent aeroelastic analysis.

Expansion of structural synthesis, analysis, and testing capabilities and the widening options available are making the choice of materials for both the airframe and the engine one that is intrinsically woven into the structural concept, detailed part design, and manufacturing process selection. A fundamental aspect, of course, is knowledge of the physical properties of these materials. Characteristics such as static tensile strength, compression and shear strength, stiffness, fatigue resistance, fracture toughness, and resistance to corrosion or other environmental conditions, can all be important in the design.

Each of these aspects must be considered and dealt with concurrently if modern structural designs for aircraft are to approach optimum configurations and, thereby, success in international

commercial competition. Thus, a successful airframe and engine structural design/manufacturing team will cover a spectrum of subdisciplines, consisting of

- advanced alloy metallurgists; constituent materials specialists with expertise in fibers, organic, metal, and ceramic matrices, and interfacial coatings;
- continuum, ply and laminate micromechanics specialists with expertise in ply property determination from constituent properties and interfacial failure mechanisms;
- continuum, ply, and laminate macromechanics specialists with expertise in elastoplastic behavior, and strength, stiffness, fatigue, and environmental behavior based on averaged properties;
- designers of structural members, components, and joints who are capable of predicting load paths, stress concentrations, and deflections and are knowledgeable about joining techniques;
- manufacturing specialists capable of choosing the optimum "raw material" form (sheet metal, dry filament, prepreg, tape, or woven broad goods); fabrication process (forging, superplastic forming, braiding, winding, tape or fabric laying, or resin transfer molding); and tooling concepts;
- quality assurance specialists, expert in the choice of nondestructive evaluation (NDE) and other testing methodologies; and
- repair specialists, dealing with operational damage in the field and "depot level" or "overhaul facility" operations using extensive facilities.

It is most important to note that current and future materials and structures aspects of aeronautical systems, both airframes and engines, require a new level of collaboration among all of these specialists. It will probably be necessary for each specialist to become more conversant with the fields in which the others work and, from the earliest stages of design, for all of these specialists to work together in ways that are unprecedented in the aircraft industry.

To summarize, the compelling reason to apply composites and other advanced materials to the structural design of the advanced aircraft envisioned in this report is to achieve the lightest weight and most effective structure possible. This includes a highly reliable structure that requires minimum maintenance and is durable under all applicable environmental influences. U.S. industry must achieve these capabilities if it is to maintain a preeminent position in the world's commercial aircraft sales and operations.

This chapter outlines the key areas of research needed and the approaches that research programs should use. Among the attributes mentioned earlier, low structural weight fraction, long life, and low costs are the principal drivers for the airframe structures of future aircraft systems described in this report. For propulsion systems, higher specific strength and ability to withstand higher temperatures are the principal drivers. These objectives, in turn, require advances in materials, structural design concepts, life prediction methodologies, and fabrication technologies. The scope of the National Aeronautics and Space Administration (NASA) structures and materials program should emphasize

- continuing fundamental research to achieve both evolutionary and revolutionary advances in materials and structures; and
- focused technology programs in materials and structures to address specific aircraft system requirements (e.g., subsonic fixed and rotary wing, and supersonic transport aircraft).

## FUNDAMENTAL, BROADLY APPLICABLE RESEARCH

Applied research in structures and materials is virtually always required at some level in developing a new type of advanced aircraft. Such applied research, specific to vehicle classes discussed in other parts of this report, is dealt with in subsequent sections of this chapter. In addition, however, there is a continuing and essential need for long-term, fundamental materials and structures research of a generic nature. An appropriate program of this kind should be guided by needs that arise in the development of generic aircraft types; it also should, by its results, change the direction of generic aircraft developments. Thus, an appropriate fundamental program of materials and structures research should seek to provide both evolutionary and revolutionary advances in materials and structures, which will be required to sustain a leadership role in both airframe and propulsion technologies. Specific areas of fundamental research that should be considered for emphasis are outlined below.

### Materials and Processes

#### **Metallics**

Metallic alloys continue to be used for more than 75 percent of most airframe and propulsion systems by weight. They constitute relatively mature and reasonably well-understood classes of materials ranging from aluminum alloys for airframe structures to nickel alloys for hot sections of turbine engines. **Continued research into metallics is strongly recommended, emphasizing tailoring of alloy systems to provide significant advances in such traditional areas as weight reduction and environmental resistance.** Aluminum-lithium (Al-Li) alloy systems, for example, promise evolutionary benefits in higher stiffness and lower density, with no reduction in structural life. Continued research efforts are required, however, to ensure that Al-Li alloys will be endowed with the balanced strength, corrosion resistance, and toughness properties necessary for cost-effective airframe structural applications. Powder metallurgy technology is another area in which continued research efforts are warranted. Aluminum powder and rapid solidification techniques offer a wider range of chemical composition and processing options, which in turn promise alloys of improved strength, toughness, and corrosion resistance, compared to ingot metallurgy processes. Powder metallurgy also has the potential of producing aluminum base alloys with capabilities to 900°F that could make them competitive with more costly materials, such as titanium, in both airframe and engine applications. Improved titanium alloys also have great potential. Alloys capable of superplastic forming continue to promise both economic fabrication of parts with complex curvature or integral stiffeners and weight savings

through reduction of stress concentrations where there would otherwise be mechanical fasteners. Research is needed to increase allowable strain rates and, thereby, part output; to reduce cavitation flaws; and to broaden the classes of superplastically formable alloys available to structural designers. Beyond more conventional metallic systems, research efforts in ordered alloys of the TiAl, Fe<sub>3</sub>Al, and Ni<sub>3</sub>Al types should be substantially increased. Emphasis should be on increasing fundamental understanding of the structure-property relations in these systems and on alloy additions to enhance strength and toughness. Both airframe and propulsion systems could benefit substantially from the high strength-to-weight potential of these more unusual alloy systems.

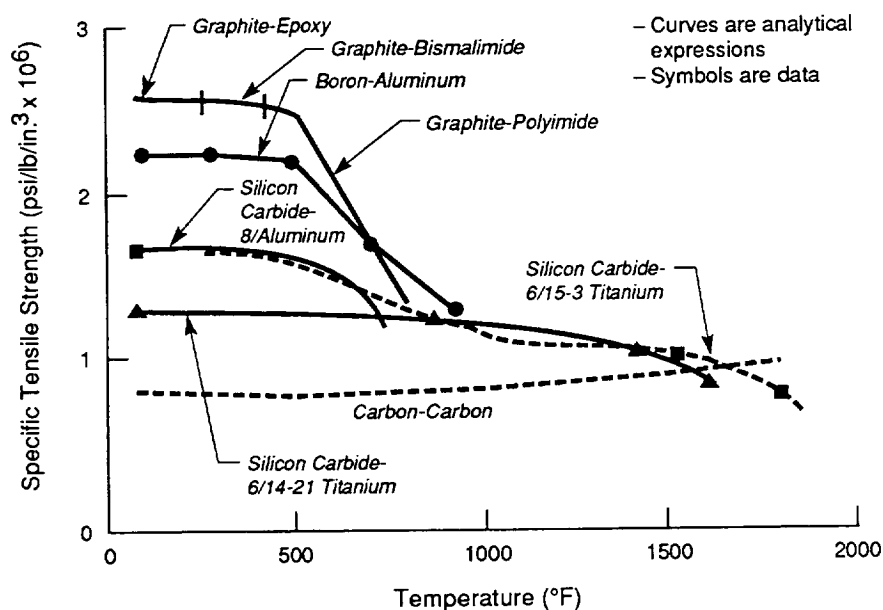
### Composite Materials

**Significant research investments are required to develop the full potential of composite materials for both airframe and engine applications.** This class of materials is, in general, very large; it includes polymer matrix, metal matrix, and ceramic matrix composites (CMCs), as well as continuous and discontinuous fibers. Various combinations offer differing advantages, depending, for example, on the thermal environment (Figure 9-1). Fibers can be entirely of one constituent material or used in combination. Some of the more traditional potential advantages of these materials are, by now, well understood. They include higher specific (relative to material mass density) strength, and stiffness, and better fatigue and fracture resistance compared to metallic alloys. Hybrid materials such as those having combinations of glass and graphite reinforcements show significant improvement in tensile fracture properties versus solely graphite-reinforced laminates. This is especially important for application to fuselage structure for penetration damage containment. Damage tolerance of these materials—particularly hybrids—is not as well understood and is an area of high potential payoff.

Polymer matrix composites research appropriately deals with both the constituent materials and the way they are combined to form composites. It should emphasize tougher matrix resins for use up to 700°F as well as novel forms of thermosets, thermoplastic, and crystalline polymers with improved processing characteristics and properties. Improvements in carbon fiber reinforcements for polymer matrix composites are expected to continue, based on the efforts of various suppliers; government research programs in this area are not likely to be required. Understanding of the fiber matrix interface characteristics required for tougher composites, however, needs to be improved, as does knowledge of how to apply textile technology, such as stitching and weaving, successfully to improve interlaminar strength. It should be recognized that a polymer matrix structure will require appropriate adhesives, sealants, and finishes.

Metal matrix composites (MMC), with either continuous or discontinuous reinforcement, have significant potential for use in both airframe and propulsion systems, particularly when operating temperatures fall in the range of 225–2000°F. **Research by NASA emphasizing composites with discontinuous reinforcements is recommended, based on the belief that such materials are likely to simplify fabrication.** Both aluminum and titanium matrix composites with silicon carbide type reinforcements (particulate, fiber, ribbon), for example,





Source: United States Air Force

FIGURE 9-1 Tensile strength per unit mass as a function of operating temperature for several composite materials.

warrant substantial continuing research and development. Technology expansion of MMCs should be directed toward tailored matrix chemistry/fiber properties for achieving consistency in high-strength/high-stiffness properties, along with practical levels of ductility, toughness, and cost. Fabrication technology, particularly for tailored structures, should be emphasized to fully exploit the advantages of MMCs and prevent cost from becoming an insurmountable barrier. Hybrid systems involving metal sheets interleaved with various types of reinforcements also show promise as structural materials.

CMCs constitute one of the highest-risk research opportunities in the materials and structures discipline. However, the magnitude of the potential benefits from these materials for higher-temperature applications, such as uncooled turbine engine components, justifies major research efforts. Both ceramic matrix and ceramic fiber technologies need to be pursued, along with an emphasis on improving fabrication technology. Achieving reproducibility in fiber quality, matrix features, and composite behavior is essential before these promising materials can be considered to have reached a state of technology readiness. It appears that ceramic materials of the silicon nitride and silicon carbide families should receive the greatest attention.

### **Structural Analysis and Design**

NASA's research efforts in structural analysis and design should focus on improving stress and deflection analysis methods; establishing proven structural dynamics and aeroelastic analyses; developing improved life prediction techniques and damage-tolerant design concepts; formulating proven methodologies for optimizing structural designs, including tailored composites; and exploiting adaptive or "smart structures" concepts. Structures researchers will have to play a stronger leadership role in working with materials researchers, both in defining priorities among material properties improvements and in adapting advanced materials to innovative structural concepts. The nation's materials and structures research program should have components considering how to cause structural, dynamics, materials, control systems, and manufacturing engineers to join in simultaneous consideration of structural, materials, and fabrication technology developments at the earliest design stages. Such "concurrent engineering" seems essential to achieving the successful application of advanced materials to aircraft structures in the time period of interest in this study.

**Improved structural analysis methods capable of exploiting the computational power that will be available in the near future should be a high-priority objective of structural design research.** A necessary adjunct of this is development of tools to reduce the cycle time for generating structural analysis models sufficiently that such analyses for both strength and stiffness can accompany the earliest structure design concepts considered by designers. Automated finite element mesh refinement and remeshing capabilities, which readily identify areas of high stress concentration and high strain gradients and allow crack propagation characteristics to be predicted should be developed and incorporated to the point of being standard features of structural analysis.

Formalized structural optimization techniques must become a standard computational tool for design purposes. Such techniques should also allow for choice among multiple static and dynamic analysis options (e.g., transfer matrix, finite element, and boundary integral methods) in unified procedures that ensure the balance between efficiency and accuracy at various design stages, which is requisite for application of these analyses to realistic designs. Integrated analysis techniques that couple structural, thermal, dynamic, aeroelastic, and control technologies are required to truly optimize a design. **Experience with optimization methods to date indicates that the state of these procedures requires fundamental research and that successful application can establish major competitive advantage in the marketplace.**

Factors such as broader ranges of flight conditions and larger applications of high-temperature structures will require methods for design and analysis that account for temporal and spatial variations in loading and operating conditions, material states, and variations of materials themselves throughout the structure. **NASA should pursue research to improve life prediction methods and damage-tolerant designs, closely linked to the understanding of individual material properties; to their compatibility in combination, particularly at structural joints; and to NDE techniques.** Structures research should take a strong lead in integrating these technical areas to achieve more efficient designs. Life prediction systems must include multiple failure mode assessments of complex, multiaxially

loaded/reinforced composite structures, by recognizing both time dependence and the need for damage tolerance. Ultimately, a probabilistic approach will be required with regard to operational loads, routine damage in service, and material properties in the delivered structure, to maximize the potential of many of the advanced materials. Stochastic analysis methods should also receive greater attention to account for more complex operational aspects of advanced aircraft systems.

Whereas the more revolutionary concepts should be taken to the proof-of-concept stage in laboratory research, composite material developments per se have outdistanced current abilities to routinely design and manufacture useful parts from them. It is important to emphasize that the research itself should often involve close and interdependent teaming of materials researchers, fabrication technologists, and structural designers. Such teamwork is increasingly necessary for cost-effective application.

## **Fabrication**

### **Resin Matrix Composites**

Composite materials and structures fabrication techniques constitute a major area of uncertainty for the aircraft of the future. The form of the precured material, the manner in which it is put together to form the desired component, its "cure," and means of assembly into the final structure all are involved. Plate or shell-like components with polymeric resin matrices tend to be "laid up" from tape or fabric that may have been preimpregnated with resin or, in the case of thermosets, have had the resin applied "wet." Relatively thin-walled cylindrical components are frequently wound, using continuous filaments or braids. Components with roughly equal three dimensionality are candidates for woven preforms of fiber that may later be injected with resins in a liquid state. Cures may be effected for thermosetting resins under high temperature and pressure (i.e., with "vacuum bagging" or in an autoclave with metal molds). For thermoplastic resins, both temperatures high enough to make them flow and molds are necessary in some instances; hot gas torches and filament winding are sufficient in others. The compatibility of desired fiber/matrix volume fraction, resin viscosity, preform density limitations, and fiber wettability are principal problems of the kind that injection cures encounter.

Whereas fabrication techniques are relatively stable in metal aircraft manufacture, there is less certainty as to the techniques for manufacture of composites. Certain technical concerns and high manufacturing cost remain overriding factors inhibiting the wider use of composites in aircraft structures, especially in cost-sensitive commercial applications. These are the principal reasons, along with design conservatism, why the potential for large weight savings and other benefits of using composites have not been realized except on a very limited basis. Applications where weight savings, fatigue life, and corrosion resistance override cost considerations have been limited VTOL and combat aircraft.

Essential to the realization of reduced manufacturing costs with composite structures is a reduction in labor costs sufficient to offset higher materials costs. This can best be

accomplished for airframes by taking advantage of the unique properties of composites to drastically reduce the number of individual parts and, thus, greatly simplify assembly processes. To minimize part count in basic fuselage and lifting surfaces, it is necessary to achieve wide spacing between stiffening members or to provide skins with integral stiffeners, or both. Reducing the parts count makes the use of sandwich skin construction attractive, relative to conventional skin-stringer construction, whether metal or composites are being used.

Sandwich construction provides the capability of carrying pressure loads and the stiffness to stabilize shear panels of large dimensions, which is necessary if wide spacing of substructural members is to be achieved. The possibility of curing composite skins simultaneously with bonding skins to the sandwich core gives composite sandwich structures one manufacturing advantage over metal sandwich construction. Reduced susceptibility to corrosion when moisture invades core voids offer another. Significant weight and cost reductions were achieved by using composite sandwich construction in the Airbus A330/A340 rudder. Weight was reduced by 20 percent and cost by 10 percent, compared with the metal design it replaced. Stabilizer, elevators, flaps, and spoilers are also of composite sandwich construction on the latest Airbus models. These are large structures; the A310/A300 carbon fiber vertical fin is 25 feet high and 25 feet wide at the base.

The Boeing Model 360 research helicopter demonstrated a large cost reduction over equivalent metal semimonocoque construction by using sandwich composite structure and wide spacing of stiffening members. Frames were placed only where major loads entered the structure, resulting in frame spacings up to 6 feet. Four longerons, with strength for limit load factor with one missing, resulted in 6-foot spacing between longitudinal bending members. Skins were Kevlar®/epoxy; the honeycomb core was NOMEX®; and the frames and longerons were largely graphite/epoxy composite. Shop man-hours to fabricate and assemble this structure were one-half as much as usual, and tooling costs were less than one-tenth those of equivalent metal structures. The simplicity of the structure produced an 86 percent reduction in the number of parts and a 93 percent reduction in the number of fasteners.

Boeing helicopter operational experience with composite honeycomb rotor blade structures on U.S. Army aircraft has been excellent. The mean time to unscheduled removal to depot was increased from 800 flight hours with metal rotor blades to 10,000 hours with composite blades. The metal blades had aluminum honeycomb structure aft of the spar, and the composite blades had NOMEX® honeycomb in the same application. Despite concern with sealing against water entry, no blade removals were associated with water entry to the NOMEX® honeycomb. Experience has also been excellent with Kevlar/NOMEX® honeycomb structure on the 1,000-gallon external fuel tanks used on Model 234 Chinooks, which have been operating in the North Sea oil fields for many years.

This background of good experience accumulated by Boeing Helicopters and others with composite honeycomb sandwich structures is still apparently unable to overcome resistance to its widespread use on the part of a large segment of the industry. Additional fundamental research and technology development is needed to broaden the data base and further increase confidence levels. Because finding an effective means to seal sandwich panels has been a particular challenge and concern, an evaluation of existing edge and surface sealing methods

used on aircraft honeycomb structures and of additional sealing methods is necessary to identify and substantiate the best sealing method for any application.

Although sandwich skins appear to have the greatest potential for reducing part count and, hence, manufacturing costs, considerable attention should be given to integrally stiffened composite structures. The term "integrally stiffened" requires definition. Simply bonding two precured parts clearly does not produce an integrally stiffened structure. Cocuring skin and frames that have been filament wound in the same operation, for example, would produce a structure that is integrally stiffened. The viewpoint taken in this report is that as long as cure of one of the components being joined to another occurs simultaneously with the joining, the part is integrally stiffened. It is not unusual to do this with uncured skins and either a cured or a partially cured ("B-stage") substructure.

Experience to date has shown that design and tooling for integrally stiffened skin panels should provide for adjustment in the position of the substructure to be attached to skins, to account for tolerances of fit-up between skin panels and frames and stiffeners, for fuselages, and for ribs and spars for wings. Uniformity of the inside surface, with tooling on the outer surface, cannot be counted on to provide good surface-to-surface conformity and, in the case of precured substructures, clamp-up stresses can cause cracking of the substructure matrix around fasteners. The tool concept developed for the Airbus fin by the German firm MBB bonds precured ribs by cocuring rib shear ties to the skins. Adjustment normal to the surface of the position of skin surfaces, with rib height, prevents prestressing at assembly. A system of aluminum blocks between skins, stringer flanges and webs, and rib shear ties provides cure pressure by thermal expansion of the aluminum. Large, integrally cocured panels are, in general, desirable to reduce the number of parts and, hence, assembly costs. However, large stiff parts present fit-up problems if close tolerances are not maintained. Much effort is needed to understand and better control the warping of large, complex parts during cure. Also, more robust joining procedures are needed.

Automated lamina placement for buildup of fuselage skins will significantly reduce costs, compared to hand lay-up, whether it be in tape or tow form. Means of doing this most cost-effectively need to be investigated. A V-22 Osprey tiltrotor aircraft fuselage afterbody was manufactured by using automatic tow placement and tape J-stringers. This method of manufacture substantially reduced manufacturing hours and provided excellent strength. All test panel failures were within the scatterband of the original, hand lay-up fabric design. Failures were instantaneous, as in the case of the fabric design. They exhibited some disbonding, which was not present in the fabric test panels, but carried equal loads before failure. Similar advantages appear in lifting surface manufacture. For instance, a "number one" composite helicopter rotor blade required approximately 15 man-hours per pound with hand lay-up. With automated lay-up, they were produced in less than 1 man-hour per pound. This is much lower than the number of man-hours expended for metal parts. With the exception of very large structures, such as the 747 fuselage constant section, 3-4 man-hours per pound after hundreds of units is typical. Thus, it appears that with proper design, remarkable cost reductions can be realized in composite part production by introducing automation to replace hand lay-up.

**In summary, NASA should undertake fundamental research and technology development for composite materials and structures, including a comprehensive investigation of the issues associated with design for manufacturing that results in reduction in parts count.** This is the key to reducing the cost of composite structures and, in turn, the key to broader realization of the weight and other benefits promised by composites. Use of the unique anisotropic characteristics of composites to produce the most efficient structures should be emphasized by using sandwich-stiffened skins, skins with integral stiffeners, and widely spaced additional stiffening elements. Manufacturing technology programs conducted for composite structures by both the Air Force and NASA have proved to be of great benefit to our national competitive position.

### **Metal and Ceramic Matrix Composites**

Metal matrix composites are, as might be expected, formed under various combinations of high temperature and pressure, and ceramic matrix composites, such as carbon-carbon, by infiltration processes such as chemical vapor deposition in a vacuum. Although more experience exists with MMCs than CMCs, both are in their infancy with regard to large-scale application.

In general, the fabrication options available are also variably susceptible to automation, most are energy intensive, and those with fine dimensional tolerances require precise molds.

### **Fabrication Summary**

To date the assembly of primary structures by composites has been accomplished with mechanical connections—for the most part, rivets or bolts. Uncertainty regarding the integrity of bond lines made outside of cocuring facilities has mitigated against bonded joints. This is also true for bonded joints in metal structures, particularly when the extended useful lives of commercial aircraft are considered.

From these considerations, it is apparent that structural design with composites is influenced to a far greater extent by fabrication technologies and materials choices than is the classical design of metal airframe structures. Superplastic forming of metallic parts is considered nonclassical in this context and raises its own challenges. Composite application to engine structure may be at least as integrated a matter as it is with airframes, but composite applications to engines until now have not been extensive enough to provide indicators. **Research in these areas, however, should be a continuing part of NASA's base program.**

### **Test Methods**

**From the wide spectrum of materials and structures tests that exist, three areas have high priority for increased research emphasis: fundamental test information, nondestructive evaluation techniques, and material lifetime properties.** First, fundamental test information is needed from which materials constitutive relationships can be developed that lead to reliable structural models of failure mechanisms. Experimental methods must be devised

to provide such data with the objectives of predicting responses to all pertinent types of loadings and states, and the total lifetimes for the structural components of interest. This class of design problem is particularly important for high-temperature applications. Materials researchers should emphasize the multiaxial, coupled nature of most materials applications to aeronautical structures and ensure that test methods for materials characterization can be performed under conditions corresponding to actual operation of the structural component. This capability does not usually exist but would be a valuable asset in the development of advanced aircraft and engines.

Second, NDE is an area of great need and promise. Many NDE techniques are available that will detect flaws and other imperfections with various degrees of accuracy and reliability. Although sensitivity and reliability of crack detection need an order-of-magnitude improvement, both NDE and the damage tolerance of materials and their applications must be advanced before efficient damage-tolerant design concepts can become routine for airframes and the critical rotating parts of turbine engines.

Integration of NDE into the structural concept/design/fabrication processes and automation of the NDE process also require greater attention. Advanced design concepts are being actively pursued that permit in situ and real-time damage assessment through the use of embedded sensor/processor technology. This approach, combined with highly damage-tolerant structures, could provide a means of assessing structural integrity over the lifetime of the component, with attendant improvement in safety and operating economics. Technology for complete automation of the NDE process over a broad spectrum of applications should be a priority research goal. This includes sensors, sensor placement tailored to the structure, and automated scanning and interpretation of results.

Third, composite materials represent new challenges not previously encountered in life prediction systems. For example, the thermal expansion incompatibilities between fiber and matrix can often be limiting in composite applications. Long-term exposure effects in composite materials are virtually unknown for the advanced systems being designed, particularly in the high-temperature regime. Testing techniques that are realistic and allow the projection of long-term effects must still be developed. Standardization of test techniques unique to composite construction should continue to be pursued. This will be especially important as new failure theories are developed consistent with the way composite materials behave.

### Smart Structures

Adaptive structures is a relatively recent concept that offers potentially important benefits in aircraft design. If, for example, a wing or wing section can be made to adapt its shape to maximize aerodynamic performance or minimize load regardless of flight regime, this could be a significant advantage—particularly if it were to reduce the number of moving parts. This technology began, in one sense, with the so-called control-configured vehicle concept and has grown to include compliant materials and structures combined with embedded sensor/processor/actuator systems. **NASA should play a major role in developing adaptive or smart structure concepts.** This research should include variable blended wing-

fuselage-engine inlet concepts, smart landing gears, active flutter suppression/load alleviation systems, and health-monitoring and field inspection procedures.

### **Durability**

Airframe durability is a systems issue focusing on economic factors. It encompasses longevity, which concerns safety and structural capability to carry load after repeated operations. Aspects contributing to durability are design characteristics leading to ease of maintenance, damage monitoring and inspection, repairability, and ultimately airframe retirement. **NASA should aggressively investigate better methods to improve structural life. The program should be composed of three parts: the determination of loads and resultant damage, including accelerated aging tests for all classes of materials; analysis techniques to assess the findings of such determinations quantitatively; and effective repair techniques to restore structural integrity when mandated.** Programs dealing with aircraft structural integrity, fleet structural management, and aircraft life cycle management and operation are important contributors in this regard, but technology advances are needed in each of these three parts of life management programs.

The same basic philosophy in life management programs is common to metallic and composite structures, but the technology advances required are different for structures composed of these two classes of materials.

### **Metals**

Events in recent years have brought the issue of aircraft longevity, and thus durability, to public consciousness, and the government has made safety evaluations of aging aircraft a national priority. In the current metallic aircraft fleet, particular concerns are disbonds in fuselage splice joints, fatigue cracks in riveted splice joints, and airframe corrosion. **Research is needed to increase the reliability and efficiency of NDE techniques, such as ultrasound and phased array imaging.**

Although fracture mechanics technology has existed for years, continued advances in understanding and capability are needed, including the ability to analyze the stress field in, and resultant fracture of, structures with multiple-site damage. This requires an understanding of various crack geometries. In addition, probabilistic structural analysis methods need to be extended to cases in which damage is present to assess residual load-carrying capabilities and lifetimes of damaged aircraft structures.

Repair techniques for metallic aircraft structures are well developed, but techniques to decrease the costs of such repairs are desirable.

### **Composites**

The use of composite materials in aircraft is relatively limited, especially in civilian applications, so the base of experience with longevity and durability is limited as well.



However, the use of composites is increasing—particularly in the Airbus 320 and Boeing 777—and so it is vital that more attention be given to issues of longevity and durability in composite aircraft structures. **NASA should lead a coordinated national program to address longevity and durability issues for composite structures.**

Nondestructive inspection techniques for laminated composite structures are not well developed in comparison to those for metallic structures. The fact that much of the damage in composite materials occurs below the surface of the structure and can, therefore, not be detected by visual methods hampers nondestructive inspection. This contrasts directly with metallic structures in which most damage can be seen. Furthermore, composite materials exhibit a number of damage modes, all of which may not be detectable if NDE is limited to one technique. An effort to develop quantitative methods for nondestructive evaluation of composite structures is clearly needed. Without this first step, assessing the residual life of such structures will not be possible.

Whereas fracture mechanics is well understood and useful for assessing damage in metallic structures, such a capability does not exist for composite structures. The multiplicity of damage modes possible in composites does not allow a single-analysis methodology to assess the effect of various possible damage states. The development of an area known as "damage mechanics" shows promise, but it is currently limited to an assessment of the stress/strain field and not a prediction of residual load-carrying capability and lifetime. The lack of a general understanding of the failure mechanisms in composite materials and structures inhibits making progress in the latter. It is clear that this understanding must first be established before progress can be made in predicting the effects of damage on residual capability.

Repair techniques for aircraft primary structures made of composite materials have been developed but are oriented mainly toward military aircraft. No similar capability exists for civilian aircraft. Furthermore, costs of repair may be the key limiting factor, including basic materials and labor costs and those needed to develop the infrastructure to handle composite repairs. A concentrated program to establish repair procedures ranging from on-site repairs, which are temporary in nature, to depot-level repairs, which are considered permanent, is necessary. Although the knowledge of the criticality of certain damage is important in assessing the need for repair, such knowledge is not necessary to develop repair techniques. Thus, such programs can proceed immediately.

Life management programs generally involve discrete inspection time intervals as determined from various analysis techniques and design philosophies. The ultimate goal of such programs should be the continuous monitoring of structures for applied loads and damage growth and associated evaluation of residual load-carrying capability. Recent technology advances indicate that this may be possible by embedding strain sensors in the structure and monitoring these throughout the use of the aircraft. The concept is particularly applicable to composite structures, because the necessary network of sensors can be embedded during the manufacturing process. Such an approach is not as straightforward, if it is possible at all, with metallic structures.

Programs in the military sector have addressed the area of "self-diagnostic structures," that is, structures that assess their own health. However, no such programs exist for civilian

applications. Numerous issues must be addressed such as the basic capability of the embedded sensors (e.g., optical fibers, piezoelastic materials, memory materials), the network of sensors and information carriers necessary, embedding techniques, and on-line analysis and assessment capabilities. However, this area holds great promise for increasing the ability of aircraft operators to assess the health of aircraft and thereby improve operational safety while decreasing maintenance costs associated with currently expensive inspection techniques such as teardown.

## **FOCUSED TECHNOLOGY ADDRESSING SUBSONIC TRANSPORT AIRCRAFT**

Materials and structures technology needs for subsonic commercial transport aircraft are outlined in this section. Emphasis is given to commercial transport aircraft, because technology benefits there offer substantially greater payoffs.

Technology advances in materials and structures applicable to commercial transport are, for the most part, transferable to other subsonic aircraft systems. However, it is important to recognize certain unique aspects of commercial transport service operations and customer relations in dealing with the application of advanced materials and structures to that class of aircraft. Flight operations per aircraft average roughly 3,000 hours annually and close to 60 hours per week. Commercial transport aircraft can be in revenue service well beyond 20 years, and the manufacturer must be concerned about safe operation. Thus, the financial risks undertaken by private companies when they introduce advanced materials and structures into commercial transport aircraft go beyond liability for passenger safety—as important as those ramifications are—and can involve structural maintenance, modification, and repair of fleets worldwide.

### **Airframe**

Lower structural weight fraction and lower costs are high-payoff aspects of advanced subsonic airframe structures. Fiber-reinforced polymer matrix composites offer the greatest potential for meeting this need. Currently, polymer matrix composite (PMC) materials have advanced to the point of wide use for fairings and doors, and limited applications in empennage and control surfaces on transport aircraft.

Although much of the basic technology is at hand to produce a commercial transport aircraft with a large percentage of composites in the primary structure, there are three significant areas of concern. First, the current cost of producing composite structures is on the order of two to three times that of comparable metal designs; second, durability, maintenance, and repair present a number of uncertainties that could appreciably affect operating cost. Finally, facilities such as large autoclaves and inspection equipment currently used to produce large composite parts and assemblies require major capital expenditures.

Cost-effective application of composite materials as a technology program must include advances in materials and structural concepts that are integrated into fabrication methods. Structural concepts that minimize part count and can be automated are essential to achieving an economically competitive airframe. Replacing skin-stringer construction with sandwich skin

panels would seem to have been a natural evolution for commercial aircraft, whether fabricated by using metal or composites. Environmental factors, however, have been determinative in choosing between skin and stringer versus sandwich construction in metal. Corrosion associated with water trapped in sandwich core spaces has been seen as an insurmountable problem. PMCs tend to vitiate this objection to sandwich construction. Further, cocuring of skin and stringer composite construction results in parts count reduction. Thus, both sandwich skins and skins with integral stiffeners promise manufacturing cost reductions with the use of composites.

The approach employed is likely to depend on the application. Sandwich skin panels for fuselages have many attractive advantages. Wings will most likely have integrally stiffened composite skins as has been done with the A-6, AV-8B, and V-22 airplanes, because of the high load intensity and stiffness needed in most wing structures. These result in skins that are too thick to be good candidates for sandwich construction. In addition, many airplane wings use every bit of available internal wing volume to store fuel. These aircraft with wet wings are not required by crashworthiness criteria to use elastomeric tank liners, as many VTOL aircraft are. In wet-wing applications of sandwich skins, there is concern about fuel seepage into core voids, certainly more concern than one has about the small amount of water in other structural components. Also of concern with wet wings is the loss of available volume for fuel due to the thickness of sandwich skins, because space for fuel is at a premium in all aircraft.

An important technological development for the future of composite structures, whether sandwich panels or integrally stiffened skin panels, is the incorporation of crack stoppers. Hybrid composite construction does promise the means to do this, with bundles of high-strain-allowable fibers interspersed at intervals among the high-modulus fibers that provide the bulk of structural properties. In addition, these structural concepts will have to meet damage tolerance and long-life requirements typical of transport aircraft. The current NASA effort in advanced composites technology (ACT) is making excellent progress toward developing the technology base for composite primary structures. **Extension of the ACT program to verify large structural components, including cost-effective fabrication as well as structural performance, is essential to bring this technology to a state of readiness for commercial application.**

**In addition to research supporting composite airframe structure technology development, research is needed in selected areas for metallic airframe structures.** These include improved structural integrity and life prediction methodology to account for the fact that the economic life of current aircraft is being extended into the future. NASA's current Aircraft Structural Integrity program is an ongoing program that addresses this need.

Improvements in engine noise for commercial high-subsonic transport aircraft have reached the point, thanks largely to higher bypass ratios and duct absorption systems, at which noise generated by the airframe is an important consideration. Cavity resonances are suspected in, for example, landing gear wells before retraction in takeoffs, and after extension in landings, as sources of pervasive, low-frequency sound.

## **Propulsion System**

The commercial fleet today is made up primarily of high bypass-ratio, turbofan-powered aircraft, whereas the next generation of commercial aircraft will be powered by advanced ducted engines characterized by very high bypass ratios. The following generation is likely to include aircraft propelled by unducted prop fans, with large-radius propeller-like blades having high and radially varying sweep, thin sections, and high solidity. Goals for all of these future products include significant decreases in fuel consumption, significant reductions in engine weight, and reduction in the airlines' operating costs for these engines and their propulsive adjuncts.

Key technologies for achieving these goals include improved materials and innovative structural concepts; both need to be addressed. Better metals, new families of engineered materials, and techniques for achieving aeroelastic stability and vibration reduction, including smart structures, all have sufficient promise to demand attention.

There will be an ongoing need for the evolutionary development of conventional metals for the particular requirements of gas turbine engine applications. In parallel, however, efforts must be directed to creating innovative, even more lightweight and efficient structures, through new design concepts that exploit the unique characteristics proposed by those engineered materials currently being studied for use in the year 2000 and beyond.

The longevity requirements of commercial products will typically be 15,000 hours for cold-section parts and 20,000 hours for hot-section parts. Engine efficiency improvements will require compressor exit temperatures higher than 1300°F and maximum turbine temperatures (uncooled) of more than 3000°F. These form the basis for advanced materials goals.

The families of materials to be considered for engine applications, in the general order of increasing temperature environment, are PMCs, aluminum MMCs, advanced titanium alloys, titanium MMCs, superalloys, titanium and nickel aluminides, intermetallic matrix composites (IMCs), and CMCs. **NASA's program should emphasize PMCs, MMCs, the aluminides, and CMC-type materials.** Specific materials and structures needs are identified by component in the following sections.

### **Rotating Systems**

#### **Fans**

Future fan sections will require lightweight fan blade materials, rugged enough to survive damage by foreign objects and erosive elements. Historically, titanium has been the major compressor material in advanced subsonic aircraft. Ducted fan blade diameters are increasing, due to increasing requirements for thrust and propulsive efficiency. Such blades are shroudless and swept for aerodynamic efficiency. The continuing challenge is to design blades that deliver improved performance, whether composite or hollow titanium whose construction is capable of withstanding the loading associated with bird impact. Robust manufacturing processes must be developed for these new blades, with recognition of the structural and aerodynamic requirements. In-service inspectability and repairability are also issues of importance.

Aeroelasticity considerations in fan blade design continue to pace the technology. Flutter-free blades, both ducted and unducted, depend on developing advanced computational analytical design systems, probably utilizing unsteady CFD techniques. Current aeroelastics technology leads to first-stage blades with lower aspect ratios than desirable based on weight goals. Improved understanding of both flutter and resonance stress problems is required to achieve higher aspect ratio blade designs and reduced weight. Improved resonance stress prediction capability is also needed for such advanced designs. **NASA/industry cooperative efforts are essential in improving the technology of fan design.** In addition to cooperating in the development of analytical tools, government test facilities will be required to generate benchmark test data for substantiating and calibrating these new tools.

### Compressors

The cycle selected for advanced engine designs will depend on the temperature level permitted at the exit of the high-pressure compressor. Higher allowable temperatures result in higher cycle pressure ratios and associated improvements in core thermal efficiency.

As with the fan section, titanium has, in recent years, become the major compressor material. Lightweight, higher-temperature materials hold the key to increasing compressor exit temperatures. Disks and/or drums make up a major portion of high-pressure compressor weight. MMC disks should provide the improved temperature capability desired. Managing the cost to manufacture these disks will be crucial; ensuring long-term reliability will be essential (through damage tolerance and adequate creep resistance); and providing efficient joining techniques, which allow the rotor to be built up from many individual pieces, will be necessary. **Joining technology for these applications is not currently receiving adequate attention.**

Reinforcing compressor disks with composites provides a good example of how new concepts can exploit the properties of composites. The stress field in a disk varies considerably from the bore inner diameter to the outer rim area that retains the blades, due to the effects of centrifugal loads and radial thermal gradients. The bore of the disk is primarily stressed in the circumferential, or "hoop," direction. Orienting fibers in the circumferential direction in the bore would be an efficient use of such materials. This approach will produce a thinner disk bore with a faster thermal response characteristic, thereby reducing the critical bore-to-rim transient thermal gradient and associated stresses.

Several materials are available for compressor blades. Conventional nickel-based superalloys (probably cast, to keep cost low) and titanium MMCs are two promising choices. The challenge is to find usable techniques for attaching these blades to the advanced material disks. Advanced joining techniques should be exploited to eliminate conventional but inefficient dovetail attachments and to exploit more fully the capabilities of advanced blade and disk materials.

## Turbines

Since turbine-powered aircraft entered commercial service, temperature capability at the turbine inlet has been increasing steadily. In the 1960s, advanced cooling technology permitted a significant increase in the allowable operating temperature. This trend to higher temperatures has been paced by increases in bulk material temperature capability increases. To make further significant increases in overall temperature capability, even greater increases in bulk material temperature capability must occur. It is expected that CMCs will provide that necessary increase. CMCs in airfoils, disks, and engine cases should allow turbines to be operated at increased temperature without the inefficiencies associated with cooling.

The progressive substitution of ceramics and CMCs for metals in the hot section of aircraft engines could begin late in the 1990s and continue for the next few decades. To bring this about, it will be necessary to create a technology base to improve ceramic and CMC material reliability and producibility, while developing the concomitant design methodologies and life prediction systems. Building this base will require efforts to understand the relationships among materials, their processing, microstructure, and properties. It will include applying this understanding to developing design tools to deal with materials with reduced ductility compared to today's experience. Other areas of concern include improving oxidation resistance, ensuring compatibility of the fiber/matrix interface, and developing CMC fabrication technology. It is important to note that CMC development has the potential to be one of the highest-payoff materials programs for advanced engine systems.

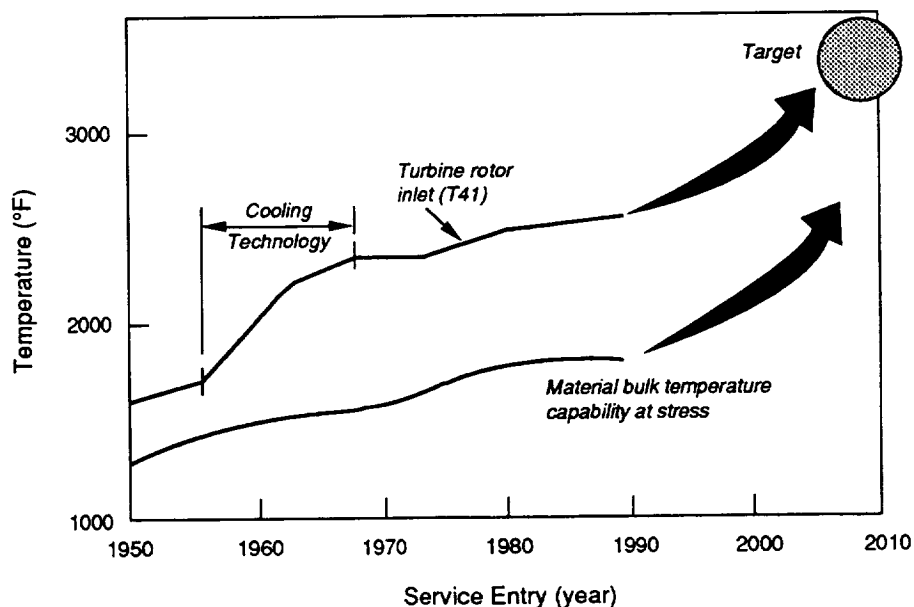
As in compressor applications, additional turbine structural challenges include developing new design concepts that capitalize on the unique properties of composite materials. Here, too, conventional blade attachment "firtrees" must be replaced with mechanical schemes that exploit the directionality of engineered material systems. These advanced concepts will likely be revolutionary rather than evolutionary. Integrating the disciplines of material sciences, mechanics, structural, design, and manufacturing process development will be essential to the success of this enabling technology.

## Shafts and Bearings

Advanced engine core sizes will continue to get smaller. The challenges resulting from this trend involve higher rotor speeds, smaller disk bores, restrictions on maximum low-pressure shaft diameters, and very high-speed bearings. This will require flexible high-speed shafts, which in turn will drive the need for active control of rotating system response to minimize damaging loadings on the engine structures themselves and the aircraft structures to which the engines are attached. Higher bypass fans will operate at lower speeds and may need to be coupled to the low-pressure turbine through a gearbox. This suggests an increased oil supply for cooling the gearbox and an enhanced cooler design.

Advanced technology engines will probably incorporate magnetic bearings instead of rolling contact bearings for the performance (5 percent) and weight improvements (10–15 percent) possible through their use. New systems will also incorporate electric starters/

generators on the high-speed rotor and feature all-electric accessories. Advantages of magnetic bearings and all-electric accessory systems include elimination of the oil system, elimination of the tower shaft and gearbox, simplified packaging of engine external components, reduced friction losses, higher rotational speeds, active shaft damping, and higher bearing operating temperatures. Figure 9-2 shows the expectations for increased temperature capability of bearing



Source: General Electric

FIGURE 9-2 Expected temperature capability of turbine engine bearing systems as a function of service entry year.

systems as the level of technology increases. The majority of the basic technologies for applying magnetic bearings are currently being developed; however, miniaturization of digital electronics will be required to bring this technology to commercial application. In addition, magnetic wiring installation with sufficient temperature capability must be developed.

### Nonrotating Components

#### Engine Cases

Application of composite materials to engine static structures will be highly dependent on the ability to design and manufacture these complex structural shapes and to provide means for determining their remaining life after years of use. Fan exit frames, for example, incorporate large-diameter rings interconnected by aerodynamically shaped struts that, in turn, are attached to inner rings forming the flow path for exit of the engine fan stream. This is yet another example in which effectively integrating structural design efforts with both

manufacturing process development and the development of maintenance procedures will be crucial to the successful incorporation of composites. The materials being developed for rotating structures in the compressor and turbine sections of the engine are very likely to be applicable to major cases as well. However, for maximum benefit in case applications, the details of the design and the orientation of fibers may well require specialized development.

### Inlets and Nacelles

Because inlets and nacelles have increasingly large diameters, the need to reduce weight is the primary driver for the structural designer. They clearly must be made of composites if advanced engine weight goals are to be achieved. Their temperature requirements are modest, so that polymer matrix composites can be applied. The major challenge will be to develop the materials and structural concepts that will be cost-competitive. The need to incorporate noise suppression treatment in these structures will continue in the future. In-service inspection and repair techniques must be developed concurrently with component development.

In addition to the environmental aspects of noise reduction, techniques must be developed for dealing with the acoustic loads produced in inlet and exhaust structures. Improved methods for predicting load generation and structural response in acoustic environments should be explored. Materials with high specific damping, capable of functioning at moderate and high temperatures, are required to ensure inlet and exhaust structure durability and reduce noise transmission.

### Acoustics

Community action barriers to the needed growth of the airline transport system are likely to be based primarily on the environmental noise generated by large, subsonic commercial transport aircraft in the vicinity of airports. Of major importance is the availability to manufacturers of the acoustical information needed to make appropriate design choices, and the methodologies and data bases required to substantiate predicted levels to the regulatory authorities and to the communities affected. It is equally important, on the other hand, that appropriate noise information, including subjective response surveys, be available from unbiased authority to help ensure that evolving noise regulations are established on sound technical and environmental bases can be met with practical configurations and without incurring unacceptable costs.

Both external and internal noises are matters of concern with unducted, so-called ultrahigh bypass fan propulsion systems. To a first approximation, the thrust generated, blade radius, helical tip speed, blade area, and number of blades determine the sound pressure levels generated. Airfoil thickness, sweep, interaction with the airframe-induced flow field and blade phasing can make lesser differences; flight paths and counterrotating arrangements, either of which can cause blade vortex intersections, can result in greater changes in noise levels.



## FOCUSED TECHNOLOGY ADDRESSING SUPERSONIC TRANSPORT AIRCRAFT

Materials and structures technology needs for supersonic aircraft are outlined in this section. They generally follow the technology requirements defined in the studies being conducted for the NASA High-Speed Civil Transport (HSCT) program. The HSCT is a high-performance aircraft in which weight is a key factor. Thus, technologies that reduce weight are important technical drivers.

### Airframe

For the HSCT airframe structure, specific material requirements are dependent on cruise Mach number, which could range from 1.8 to 2.4. At higher Mach numbers, materials with a 300–350°F temperature capability are required.

Neither the higher dynamic pressures nor the higher temperatures associated with a speed of Mach 2.4 give rise to important design considerations that are new in the aircraft design field. Although considerably above current subsonic requirements, these temperatures and speeds are in the range of currently designed military aircraft. They do, however, involve design criteria not dealt with in previous large U.S. commercial transport aircraft structures. These include the possibility of panel flutter, large temperature gradients across airframe structures during acceleration and deceleration, and very thin wing sections. An economic objective of the HSCT program is to achieve an airframe weight reduction of up to approximately 30 percent relative to Concorde-generation designs. The importance of achieving this weight reduction cannot be overemphasized. Not only are operating economics directly affected, but current runway/taxiway infrastructure limits are estimated to be 900,000 pounds, and each pound of empty weight added in the design stage grows to several times that in takeoff gross weight.

Although the drive for a low structural weight fraction places PMC materials in the lead role, advanced titanium is competitive in compression applications. High-temperature aluminum may also play a role in certain applications because of the relatively low cost. Titanium alloys are available that would meet all technical requirements, but considerable effort must be expended in research and development to further improve their engineering properties and reduce fabrication costs. These advances could lead to their widespread use. Thus, the materials technology program required to meet HSCT requirements should focus on PMC, advanced titanium alloys, and the development of cost-efficient design concepts for titanium and hybrid laminates.

Currently, there are no proven PMC materials or aluminum alloys capable of 60,000 hours of service in an airframe structural environment at temperatures in the 225–375°F range. Because it is usually necessary to demonstrate twice the expected lifetime, the materials requirement for HSCT will be difficult to meet. Some seven to eight years of testing is required just to validate the 60,000-hour life capability of a material under HSCT airframe thermal and mechanical loads and real-time temperature conditions. The development of accelerated testing procedures and modeling techniques for thermal, thermal-mechanical, and environmental degradation mechanisms is vital to developing and characterizing new materials. Materials

development testing and validation for this service environment should be a high priority in the technology program. Some specific recommendations are outlined in the following sections dealing with each class of materials.

### **Polymer Matrix Composites Technology**

PMC technology development should include high-temperature thermosetting and thermoplastic matrix resins. Significant improvements in both processability and high-temperature stability are required for the HSCT mission. Most likely, a major breakthrough in resin technology will be required to achieve the combined technical performance with the ease of fabrication necessary to produce cost-effective airframe structures.

As in the case of subsonic transport aircraft, cost-effective application of PMCs for HSCT will require an integration of material advances and structural concepts into cost-effective fabrication methods. Structural concepts that minimize parts count and can be automated are essential. The most demanding aspect of an HSCT regarding airframe structure is the fuselage. The use of sandwich construction is desirable, because it is very efficient and provides good heat insulation for the cabin area. Pressurized fuselage concepts that preclude cabin decompression are essential for an HSCT that cruises above 40,000 feet. Special wing configurations are likely in an advanced HSCT to minimize sonic boom footprints and provide laminar flow control. These needs will also require innovative solutions by the structures community.

In addition to the materials and structures developments noted above, substantial efforts will be required to verify combined advances in materials and structural concepts. This activity is likely to include many subscale tests leading eventually to near full-scale testing.

### **Aluminum Alloys**

Current ingot metallurgy aluminum alloys are limited to 200–225°F. Increasing the temperature capability of these alloys another 100°F to meet the higher HSCT requirements is difficult. However, recent advances in powder metallurgy aluminum alloys show excellent potential for achieving the higher-temperature capability. This approach is more costly than ingot metallurgy alloys, but should be pursued together with advanced ingot metallurgy approaches. Microalloying and particulate reinforcement are promising approaches to make ingot aluminum alloys satisfactory for certain HSCT applications.

A successful, economically competitive structural design will involve a combination of materials in the airframe. The higher speeds will place greater emphasis on achieving compatibility among components with different thermal coefficients of expansion. There is a large difference between the thermal coefficients of expansion of composite materials and those of metal components. Unless proper design concepts are developed, these differences could result in significant internal stresses as the temperature environment changes for major structural components.

**Materials and structures research and development effort in support of the HSCT needs to be directed toward**

- developing basic composite and metallic materials that can operate in the range of 225–375°F, have durability and toughness properties that can resist degradation in the operational environment for 20 years, and can be reliably produced at minimum cost;
- establishing design concepts that save significant weight relative to current metal structures and can be economically fabricated; and
- verifying materials developments, design concepts, and fabrication technology by producing large-scale components that can be subjected to laboratory or, preferably, full-scale service testing.

The present NASA program embodies many characteristics needed to achieve these goals, but the major emphasis to date has been on subsonic aircraft requirements. Much of technology development involving new structural concepts is applicable to both subsonic and supersonic designs, but the research program should be balanced to ensure that materials and manufacturing process development will include those compatible with the more extreme requirements of the HSCT.

### **Propulsion System**

Most of the advances noted in the subsonic aircraft section for rotating components (compressors and turbines) are also required for the HSCT. In addition, special developments in the inlet, combustor, and exhaust nozzle are required for the HSCT. They are described in the following sections.

#### **Combustors**

The exit temperature of the high-pressure compressor and the combustor associated with supersonic cruise translate to an HSCT mission in which 80 percent of operations are at maximum temperature. Current subsonic commercial aircraft typically fly at maximum temperature for less than 10 percent of the total mission time. Operating at extremely high temperatures over such a long portion of the flight reinforces the need to develop high-temperature materials for the HSCT combustor. Additionally, the materials system selected for combustors must have good high-cycle fatigue resistance to withstand significant acoustic and vibratory loads.

In other respects, combustor materials needs for HSCT are similar to those of advanced subsonic commercial transport applications. In either case, it is essential that the engines satisfy low nitrogen oxide ( $\text{NO}_x$ ) requirements. Advanced combustors can be expected to have (1) decreased liner cooling flow or no cooling at all, (2) staged combustors, and (3) turbine inlet temperatures of at least 3000°F.

CMCs capable of operating to 3000°F are likely candidate materials for the combustor. CMCs offer the high-temperature performance of monolithic ceramics with improved toughness and reliability. For CMCs in which the matrix modulus is high relative to the fiber

reinforcement, material toughness is likely to be dominated by the fiber/matrix interface and its characteristics.

High-conductivity, high-strength silicon carbide and silicon nitride composite systems have the potential to meet current projected combustor material requirements. Improvements in silicon carbide fiber capability are needed to increase high-temperature strength retention and composite structure creep resistance. Materials processing is a critical part of advanced CMC development, and it must be addressed concurrently with combustor materials selection and evolution of the design. Processing approaches could vary considerably, depending on the matrix, fiber, coating, and material form (such as weave) selected for the combustor.

In addition to materials with higher-temperature capability, structural concepts must be developed that avoid high thermally induced strains at points of attachment. Advanced aerothermal and structural computational codes are likely to be needed to achieve optimized designs, and appropriate testing is required to prove the feasibility of advanced combustor configurations.

### **Nozzles**

A key technology area for many jet aircraft types, but for the HSCT in particular, is the design and manufacture of the exhaust nozzle. This component must be lightweight, designed for high propulsive efficiency, and include sonic treatment for noise control. Alternative nozzle designs being considered for the HSCT all represent a significant percentage of the installed propulsion system weight. By their nature, these low-noise exhaust nozzles are large, mechanically complex structures running at elevated temperature, with large gas flows and pressure gradients.

Development of a practical nozzle configuration is highly dependent on the simultaneous development of advanced, high-strength materials and associated structural concepts that exploit the use of composites. They must perform uncooled to the maximum extent possible to avoid performance losses associated with cooling large surface area liners. In addition to meeting challenging temperature and strength requirements, the materials selected must allow fabrication into the large, complex shapes currently being studied. The materials systems being considered currently have low ductility in general and, thus, may be difficult to fabricate.

Advanced nozzles are likely to be produced from several different materials. A very wide range of maximum temperatures and a wide range of specific strength requirements will be encountered, depending on which part of the nozzle is considered. No single material system is likely to have superior properties in comparison to others over this entire strength-temperature range. Carbon-carbon composites have high specific strength and stiffness and adequate temperature capability, but exhibit poor oxidation resistance uncoated. It will be necessary to develop an effective coating that prevents oxidation before further exploitation of this otherwise highly capable material is possible.

CMCs will probably be employed in the part of the nozzle exposed to gas path exhaust temperatures. IMCs will make up many other parts of the structure. This is an enabling technology for the HSCT. The materials development done in support of this nozzle will have

high payoff for other sections of advanced subsonic engines, once feasibility has been established.

## **FOCUSED TECHNOLOGY ADDRESSING SHORT-HAUL AIRCRAFT**

Short-haul aircraft are thought of in three subcategories: commuter aircraft, rotorcraft, and general aviation (GA) aircraft. The associated propulsion systems in the 2000–2020 time frame have no substantial materials and structures problems that differ from those of other subsonic aircraft. Accordingly, this section refers solely to airframe aspects of short-haul aircraft.

### **Commuter Aircraft**

Commuter aircraft, rotorcraft, and GA airplanes are included in the short-haul category. Commuter aircraft range in size from 19-passenger turboprops to 65-passenger turboprops and 107-passenger jets. Although more are in service, today only two commuter types are being manufactured in the United States, the 19-passenger Beech 1900 and the Fairchild Metro. All others are of foreign design and manufacture.

Low-weight composite and/or superplastically formed metallic airframe structures, with costs substantially below those of aluminum structures, could provide a competitive edge, helping U.S. manufacturers to compete in the short-haul market. The need for structural research to achieve these low-cost structures is common to the activities identified for all subsonic aircraft fuselage and wing structures. Aside from a general trend toward greater simplicity, and more lightly loaded structures as aircraft become smaller, there are no unique structural issues specific to commuter aircraft.

### **Rotorcraft**

Civilian use of rotorcraft consists primarily of helicopters, although tiltrotor aircraft are under development and proposed commercial versions show promise for the commuter market. Structural research aimed at low-cost, low-weight composite fuselage structures will benefit the rotorcraft industry greatly. However, unlike commuter aircraft, rotorcraft involve a number of unique structural issues that impede development and successful application to commercial operations.

### **Vibration and Noise Reduction**

Rotorcraft vibration is a source of both passenger resistance and fuselage fatigue damage. Rotor noise has low-frequency components that are both distinctive and penetrating. It is an important factor in community acceptance. Rotorcraft vibrations can be reduced through aeroelastic tuning of the rotor, but this very complex procedure has not been entirely mastered. However, increases in computational power and the advent of formalized optimization

procedures now make substantial advances possible. Active, higher harmonic rotor control, including the possibility of individual blade control, can reduce helicopter and tiltrotor vibration and rotor noise caused by blade-vortex intersections. In addition, active rotor controls can reduce vibrations generated by the rotor of tiltrotor aircraft in cruise flight, which are caused by rotor operation in the wing's nonuniform flow field.

### **Suppression of Tiltrotor Aircraft Whirl Flutter**

The highly coupled behavior of the tiltrotor aircraft's rotor and the flexible wing on which it is mounted calls for active control applications to suppress whirl flutter. This might reduce wing weight by 35 percent, since tiltrotor wing structures are sized for whirl flutter torsional stiffness requirements.

### **Damage-Tolerant Structure for Dynamic System Components**

Alternate rotor hub designs taking full advantage of composites technology for tiltrotors and helicopters promise to significantly reduce drag and weight and improve rotorcraft reliability and maintenance. Drive system components also could benefit from such applications, particularly where supercritical shaft system designs make mechanical redundancy feasible. Gear failures for some helicopter types are the largest single source of fatalities. Double vacuum melting of gear steels has greatly increased the size of crack that will not propagate in fatigue. Additional development is necessary to improve this further, with the attainable goal of completely eliminating in-service fatigue failures for these components.

### **Design of Transmission Components**

Useful experience has been gained in fabricating composite gearboxes with heavily loaded covers—in this case, a helicopter rotor gearbox. The rotor gearbox transmits all flight loads from the rotor to the airframe. Recently, one was designed to be built with composites. Its cost, however, was marginal for production use at approximately 25 man-hours per pound. By way of comparison, the cost of an aluminum fuselage structure would be 22 man-hours per pound on a comparable basis (i.e., for the first prototype in both cases). Production costs, of a learning curve effect is assumed, would be much lower; the application of automated methods could produce further fabrication cost reductions.

Gearboxes and similar mechanical parts that are neither primarily cylindrical, like shafts, nor flat, like lifting surfaces, would seem to be much less amenable to automation. Automated lay-ups and filament winding are probably unsuitable, so such parts may require more innovative systems of automation. Woven preforms and resin transfer molding may make it possible to achieve, for such components, both the fail-safe aspects and the weight reduction that are so desirable for improving safety and performance, together with the low-cost advantages of automated manufacturing.

### General Aviation

The structural research aimed at low-cost, low-weight composite structures, as discussed elsewhere in this report, will also benefit general aviation. Special attention needs to be given, however, to structures that are so lightly loaded that problems of minimum gauge arise for skin material and for ultralow-density sandwich core material.

Rejuvenation and enhancement of NASA's effort on noise for propeller-driven GA products can enable an improvement in the environment of GA airports and can possibly improve the competitiveness of U.S. aircraft in this category.

### **REGULATORY REQUIREMENTS**

The ability to demonstrate compliance with Federal Aviation Administration (FAA) airworthiness requirements is essential to the usefulness of any aircraft structure intended for civil operations. Demonstration of airworthiness is a special challenge when new and different materials and structural concepts are involved; this includes, of course, composites. An element of growing importance in this area is continued airworthiness over the life of the aircraft, because the useful lives of aircraft have increased greatly in recent years.

Airworthiness requirements fatigue resistance, fail-safe characteristics, damage tolerance, inspectability, repairability, and resistance to environmental effects require major attention in the nation's materials and structures technology programs. This should include consideration of how compliance with airworthiness regulations can be demonstrated on a practical basis during aircraft certification programs. If well-defined and accepted methods and criteria for demonstrating airworthiness compliance are lacking at the time of aircraft development, factors of conservatism are likely to be imposed which are so large that the advantages of improved materials or structural concepts are lost. The alternative could be an unacceptable delay in the certification procedure.

Consistency among civil, military, domestic, and foreign airworthiness authorities is a major factor in a decision to apply a new material or new structural design approach. Manufacturers are understandably reluctant to undertake a design unless all airworthiness authorities potentially involved have accepted the technical basis of the design. **With its substantial contributions to both civil and military aircraft developments over the years, NASA can play a pivotal role in establishing consistency in airworthiness standards.**

U.S. regulatory agencies have in some cases set specific requirements that are not consistent with technical principles accepted by other agencies, often as a result of inappropriate reaction to in-service problems. An example of this is the prohibition by one of the military services of the use of nonmetallic honeycomb in primary structures and of any use of Kevlar®. These prohibitions were based on experience with poorly executed designs. Extensive, highly satisfactory service experience with other designs has shown these prohibitions to be unwarranted.

Differences among airworthiness criteria applied by different authorities in damage tolerance requirements for composites are another area of concern. These differences need to be resolved.

## CONCLUSIONS

The most important conclusions arrived at in the materials and structures discipline are summarized here, without consideration of the auspices under which the advances should be accomplished.

### Advanced Materials

Composite fiber and matrix materials developments today contrast with the situation that existed during the evolution of aluminum. The gradual dominance of aluminum as an aircraft material was seen by aluminum manufacturers as only one of a great many potential uses, which included large-scale consumer product manufacturers. The relatively low volume required for any one of the many advanced airframe and engine materials today poses a problem for the materials development industry. Economics dictate that this industry concentrate on materials research and development for applications of the largest scale. This makes a persuasive argument for government involvement in advanced aerospace materials research and development in the 1990s. Furthermore, the time between conception and application of new structural materials is very long, largely because ultraconservatism must be exercised by responsible structural designers. There is also a need for extensive data bases adequate to ensure substantiation.

### Airframe Applications

Manufacturing economics is one of the serious roadblocks to the use of advanced composites for the airframe structures of subsonic transports, short-haul aircraft, and rotorcraft. This situation will continue until major improvements are made in integrating design and manufacturing with composites.

Beyond integration, however, composite applications to primary structures, such as wings and fuselages, will require extensive development of individual engineering design, tooling, and manufacturing techniques if the industry is to realize the weight benefits possible for advanced subsonic transport and HSCT aircraft. Even then, the pace and direction of past and current programs indicate that composite applications to primary structures such as wings will be easier to implement, whereas fuselage applications will be more difficult.

Foreign competitors are applying composites and superplastic forming of metals aggressively and are gaining valuable experience in their use in structural design. Improving U.S. application of composites, advanced metallics, and superplastic forming, to a lesser extent, will improve weight and cost, and is necessary to improve our competitive position.



HSCT airframes will require application of mixed materials because of the wider temperatures variation that will be experienced by the airframe in normal operations. Although not as high as those routinely experienced by engine hot-section parts, portions of the HSCT airframe will be subjected to temperatures beyond all commercial transport airframe experience to this time (except, possibly, the Concorde). Because HSCT airframes will involve quantities so much larger than occur in engine applications, economics will be a key factor. Thus, innovative uses of advanced alloys of titanium, new classes of aluminum, and resin matrix composites that can withstand high temperature will be required if HSCT configurations are to be successful.

### **Engine Applications**

New, high-temperature-capable materials needed for advanced engine developments are often cited as including metal matrix composites, ceramics, ceramic matrix composites, and intermetallics. All of these advanced materials hold considerable promise, despite their high costs, of jet engine nozzle applications—particularly in HSCT aircraft. Variable exit nozzle cross sections, required for propulsion efficiency over a wide speed range, for example, call for both stiffness and strength at high temperature. Furthermore, the likelihood of aft location makes nozzle weight a matter of importance for flight stability in all cases and for aeroelastic stability in configurations with wing-mounted engines.

The use of MMCs such as silicon carbide/titanium for reinforcing high-pressure stage disks in axial compressors appears to be promising as well. Stiffness and strength at moderate temperature are required to carry the heavy "hoop tension" created by centrifugal and thermal loads, and light weight is always particularly important in rotating machinery. All of the promising MMC applications, however, require that substantial structural design and manufacturing research go hand in hand with materials development.

The extent to which CMCs become available will depend on progress in two distinct types of research programs that can profitably be pursued in parallel: namely, fundamental materials research to increase the toughness of CMCs, and structural design and manufacturing research to find applications that take into account all the limitations of present-day CMCs. Such applications seem most likely in turbine engine combustors, first turbine stages, and nozzles.

Intermetallics represent a new and promising source of high-strength, high-temperature-capable structural materials. Bringing candidate intermetallics to the point of practical application, however, will require fundamental metallurgical research, especially to achieve acceptable levels of damage tolerance.

Exploitation of composite materials of virtually any kind will require new techniques of joining built-up rotor stages and joining rotor blades to disks. Competitive designs for advanced rotating parts will depend on such exploitation and on improved understanding of flutter and resonance stress problems and application of magnetic bearing technology.

### **Smart Structures and Active Control**

The potential of active materials in smart structures (e.g., "shape memory" alloys, piezoelectrics, and thermally responsive composites) seems strong for achieving advanced methods of structural integrity diagnosis for safety improvement and maintenance cost reductions. Equally important is their promise for active control of internal noise and for reducing structural dynamic loads, stabilizing various aeroelastic phenomena having the potential for destructive instabilities, and improving crew and passenger comfort by reducing vibrations. Their impact, taken together with applications of automatic feedback control techniques, particularly in providing solutions to aeroelastic instability problems, will be continually increasing. Reduction in size, weight, and cost of the components constituting these systems, through fiber optics, microprocessors, and smart material sensors and actuators, will allow the redundancies necessary for operations in keeping with commercial transport safety standards.

It is noted, however, that before any diagnostic means for increasing structural integrity can be useful, the damage tolerance of composite materials needs to be increased substantially. Graphite/epoxy, for example, is a brittle material. Thus, hybrids that incorporate fibers with high failure strains should be pursued to achieve higher damage tolerance.

### **Acoustics**

Acoustics issues are of sufficient importance to warrant basic research to improve fundamental understanding and accumulate the technical knowledge required for practical application of noise control methods of all kinds for rotorcraft, high-subsonic and short-haul transports, and GA aircraft. This will require analytical methods for predicting noise generation and propagation characteristics reliably, as well as research on human reaction to noise, including sonic boom. Increased information on the effectiveness of active noise control techniques is required to an extent sufficient to allow reliable trade-offs to be made, at the design stage, among active and passive treatment alternatives, cost, reliability, and range/payload. This applies to acoustic sources of all kinds— aerodynamic, propulsive, and those generated by dynamic system components—and to both interior and exterior noise.

### **Regulatory Aspects**

The weight savings possible with composite structural materials are limited by inspection capabilities and damage design criteria. Both need additional emphasis. Differences in criteria should be addressed by NASA and the FAA to the extent that safety and reasonably competitive positions are ensured. Including the acquisition of comprehensive airworthiness data as an integral part of materials and structures research should pay great dividends in allowing early definition of realistic regulations and certification requirements, thus expediting application of new materials and structural concepts.

## **Recommendations for NASA**

### **Fundamental and Technology Development Research**

**NASA's program of basic research in materials and structures should be comprehensive, visionary, and aggressive. Particular attention should be given to improving the understanding of failure modes in composites, increasing their damage tolerance, and advancing means of nondestructive evaluation.** In addition, attention should be given to further development of aluminum and titanium alloys, as well as hybrid laminate materials with aluminum and titanium sheets interleaved with various organic and ceramic materials.

All advanced composite materials applications to aircraft structures require that design and manufacturing developments proceed hand in hand from the earliest stages. **NASA should have an important role in bringing about this cultural change by conducting innovative structural design and manufacturing research for both airframes and engines in a program conducted jointly with industry. NASA's investment in fabrication technology development should be significantly greater than is characteristic of recent times.**

**NASA's materials and structures program, in cooperation with the Department of Defense and the FAA, should be a major force in establishing the data base requisite to realistic regulations.** Each technology project should include explicit consideration, at the least, of how it can contribute to the technical basis for airworthiness regulations that will provide safety at minimum cost. Close and frequent contact between NASA materials and structures researchers or technologists and airworthiness engineers from the FAA is clearly required and could pay great dividends in the speed and efficiency with which new materials and structures approaches can be put into production and service.

### **Airframe-Specific Research**

**The cost-effective application of composites to primary airframe structures, including wings and fuselages, should be a research program of high priority for NASA.** NASA's programs should emphasize structural design technology that reduces part count, primarily through sandwich and/or integrally stiffened panels, and improves the efficiency of major structural joints. Research supporting superplastic forming technology should be continued where it promises to advance these objectives. A necessary component for composites research, particularly, should be environmental aspects (e.g., moisture and thermal effects) and the means to ensure safety and long-term integrity in their presence.

**NASA's program of materials and structures research for the HSCT should give high priority to developing basic composite and metallic materials and design concepts for 225-375°F operations** that save significant weight relative to current metal structures, can be produced at costs acceptable for airframe applications, and have durability and toughness that resist degradation for 20 years of operation. This program is seen as involving large-scale test components and, preferably, full-scale service testing. Among NASA's HSCT research efforts

should be the development of generic design concepts accommodating combinations of materials with mismatched thermal coefficients of expansion.

**Automated sensing and feedback control should be an increasing part of NASA's research program, capitalizing on smart structure advances**, including distributed sensing and strain-actuated materials to achieve structural and acoustic treatment weight reductions in a variety of potential applications. These may encompass, for example, stabilizing aeroelastic phenomena, internal noise suppression, and rotorcraft vibration reduction.

### **Engine-Specific Research**

**NASA should assign highest priority, in its long-range engine materials research program, to the development of ceramic matrix composites, including fabrication technology.** Substitution of CMCs for metals in engine hot sections is likely to occur in the next decade, and NASA should lead the way.

**The introduction of metal matrix composites into high-pressure compressor disks deserves major emphasis in NASA's engine programs for the nearer term. Similar research in the turbine area merits emphasis, as well.** In both areas, NASA should pursue means of reducing manufacturing costs—particularly as regard to new techniques of joining, both in built-up rotor stages and in joining blades to disks—and ensuring long-term reliability, as well as increased temperature capabilities and reduced weight.

**Intermetallics should continue to be an active part of NASA's engine materials research for the longer term, with emphasis on improving damage tolerance.**

### **Acoustics**

**NASA should lead the nation, with program levels reflecting the importance of noise to civil aviation, in aeronautical acoustics research** to (1) improve the understanding of its sources; (2) accumulate the knowledge required for application of noise control methods; (3) develop analysis methods for predicting noise generation and propagation and for evaluating noise reduction methods; (4) improve understanding of human reaction to noise; (5) arrive at reasonable criteria; and (6) develop active noise control techniques to the point at which reliable trade-offs can be made at the design stage. This applies to aerodynamic, propulsive, and gear-generated noise, all aircraft types, and both interior and exterior environments.

## AVIONICS AND CONTROL

### INTRODUCTION

The 1980s saw a significant change in the nature of commercial air transportation and military aircraft operations as a consequence of remarkable growth in application of new avionics. These included widespread implementation of fly-by-wire systems and significant advances in fully electronic displays ("glass cockpits"), digital flight control and flight management, ring laser gyro-based inertial navigation, and full-authority digital engine controls.

These innovations provided much-increased functional capability without adverse impact to the weight of aircraft. In fact, despite the proliferation of avionics, they have accounted for approximately 1 percent of the airplane weight for the last 20 years.

However, advances in avionics have brought a new set of problems. For example, demand has increased for coordination and standardization in areas as diverse as microwave landing systems, software standards, electromagnetic vulnerability standards, and certification and testing requirements. Other problems include generally inadequate testing and validation to ensure that such systems meet all requirements when they are introduced, and the often massive cost and schedule overruns resulting from problems in software development and validation.

The digital systems introduced in the 1980s included box-for-box replacements or additions to existing functions. This created a proliferation of black boxes and consequent challenges to system integration, validation, reliability, and cost. There were also many technology developments occurring in other sectors that failed to find their way into aeronautical applications in a timely manner. For example, fiber optics, which have extensive applications in communications, have not yet seen significant application in aircraft. In short, although avionics and control technologies have produced continuous advances in aircraft systems, there is still significant opportunity for greater efficiency, enhanced functionality, and better integration of systems. This is particularly true for systems that reduce the burden on the crew of flying the aircraft and systems that allow for increased capacity of the global air traffic management (ATM) system. It is important, however, that system and component developers

### Recommendations

#### General

NASA should play a major role in the development and validation of the key technologies in avionics and control, including system development and integration, simulator and/or experimental flight validation, and serving in a technical advisory capacity for industry and other agencies of the government.

#### Specific

1. NASA should work with the FAA, academia, and industry to produce advances in
  - flight path management;
  - pilot/vehicle interface (i.e., establish a cognitive engineering effort in this area);
  - avionics and controls integration;
  - control function applications; and
  - aircraft power and actuation.

include a significant degree of upgrade capability to avoid obsolescence brought on by this rapid pace of technology development.

Current research and development in avionics and controls is expected to result in operational solutions to many of the problems anticipated because of air traffic growth. Techniques are being developed for the more effective use of computer automation to manage air traffic, but integration of that technology into the national or worldwide system is a major challenge. A primary hope for meeting the challenge of increasing congestion in the air and on the ground is full-scale implementation of the Global Positioning System (GPS) and differential GPS.

Emerging technologies also offer significant enhancement of the pilot's situational awareness, which is fundamental to improved safety and mission effectiveness. Again, implementation of the GPS is key to providing enhancements in this area. Panoramic pictorial presentations of the aircraft flight situation, voice-interactive communications with automated systems, and tactile augmentation for control manipulators are examples of expected advances over the next generation in pilot/vehicle interfaces. These advances in capability will be brought about through advances in integration and fusion of multi spectral sensors; large, flat-panel, color displays; miniature optics and related multiple laser projection arrays; and continued growth in computational/image processing power. However, a major issue is the ability to use this technology in a manner that truly enhances, rather than complicates, a pilot's ability to manage the aircraft and its mission. This problem is addressed in detail in Chapter 11.

The remainder of this chapter outlines in list format the key technologies that have been identified by the Committee as vital for maintaining continual advancement in the state of the

### **Benefits of Research and Technology Development in Avionics and Controls**

#### **Aircraft Operations**

- Enhanced functionality
  - Engine control
  - Aerodynamic actuator control
  - Greater situational awareness
- Smaller crew
- Enhanced safety
  - Reliable automated systems
  - Enhanced communication
  - On-board position determination/collision avoidance
  - On-board flight path management
  - On-board health monitoring
  - Enhanced controllability and maneuverability

#### **Aircraft Design and Development**

- Integrated systems
- Technology validation

art in avionics and controls. The roles that the National Aeronautics and Space Administration (NASA) can be expected to play in the development of these key technologies are identified by acronyms in the lists and have been categorized, for brevity, as follows:

R	Fundamental research
SD&I	System development and integration
V	Simulator and/or experimental flight validation
TA	Technical advisory

Fundamental research (R), of course, implies that NASA should be the primary agent for advancing the base state of the art in areas where the technology is not yet mature enough to warrant full-scale development of components or systems. The designation of system development and integration (SD&I), however, indicates that NASA should proceed, in conjunction with industry, universities, the Federal Aviation Administration (FAA), and other appropriate agencies to develop and, where appropriate, implement full-scale systems. The major new issue is system integration. Only when a full-scale system is put together are integration tasks adequately addressed. Similarly, the simulator and/or experimental flight validation (V) designation implies that NASA should be heavily involved, again in conjunction with industry and others, in providing the experimental ground facilities and flight test aircraft to prove the utility of specific technological concepts. Finally, the designation of a technical

advisory (TA) role indicates that although NASA may have significant expertise to offer in the development of a particular technology, it should be limited to a support role.

The Committee has identified five categories in which to organize the key technologies. From most general to most specific, they are as follows:

1. Flight path management;
2. Pilot/vehicle interface;
3. Avionics and controls integration;
4. Control function applications; and
5. Aircraft power and actuation.

In the sections that follow, these categories and the designators described above are correlated to show how NASA can be expected to contribute to advancing avionics and controls technologies for future aircraft. The boxed material summarizes the primary recommendations that appear throughout the chapter and the benefits that can be gained through research and development aimed at advanced avionics and controls.

## **FLIGHT PATH MANAGEMENT**

Under the general category of flight path management, the Committee has identified four specific areas of concern: (1) navigation, guidance, and performance/mission management; (2) communications; (3) collision avoidance; and (4) bad weather detection and avoidance. The Committee also considered several unique requirements for rotorcraft. These are discussed in the following sections along with very specific descriptions of the technologies that are needed to address the associated problems.

### **Navigation, Guidance, and Performance/Mission Management**

**Global Cooperative Airspace Management.** The greatest problem in global airspace management has to do with technology integration involving an overall system architecture, appropriate algorithms, and air and ground communications technology. True four-dimensional control of aircraft will be needed to enable the necessary large gains in airport and airspace capacity. Figure 10-1 shows the complexity and scope of the integration task; Figure 10-2 summarizes air traffic automation aids being pioneered in NASA research that could realize major benefits by the 2010–2020 era.

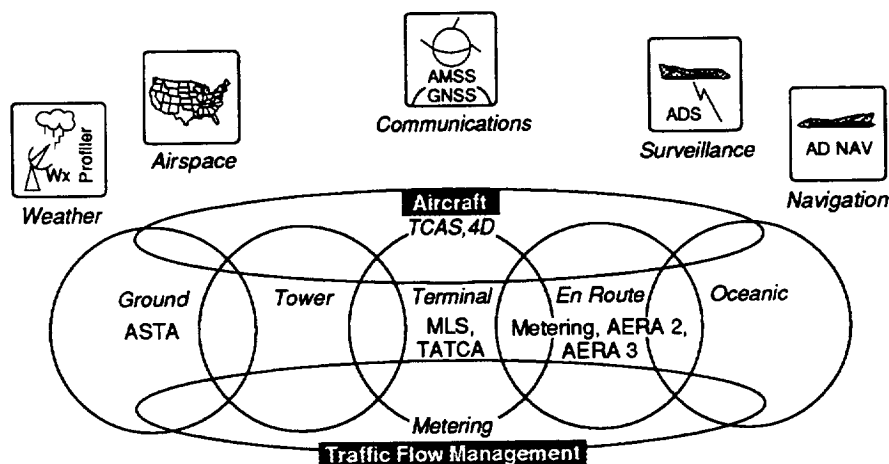
#### **TECHNOLOGY NEEDED**

#### **NASA ROLE**

Integration of individual communication elements in such a way as to ensure optimal operational capability and overall system fault tolerance (e.g., use of GPS and airborne downlink data to aid in air traffic control surveillance and traffic management)

V, TA





Key			
ADS	Automatic Dependent Surveillance	TATCA	Terminal Air Traffic Control Automation
AERA 2	Automated En Route ATC (Phase 2)	TCAS	Traffic Alert and Collision Avoidance System
AERA 3	Automated En Route ATC (Phase 3)	Wx	Weather
AMSS	Aeronautical Mobile Satellite System	4D NAV	Navigation in (x,y,z,t)
ASTA	Airport Surface Traffic Automation		
GNSS*	Global Navigation Satellite Services		

\*GNSS is a combination of GPS and GLONASS, the Soviet GPS equivalent.

Source: Boeing Commercial Airplane Group

FIGURE 10-1 Integration of elements needed for cooperative global airspace management.

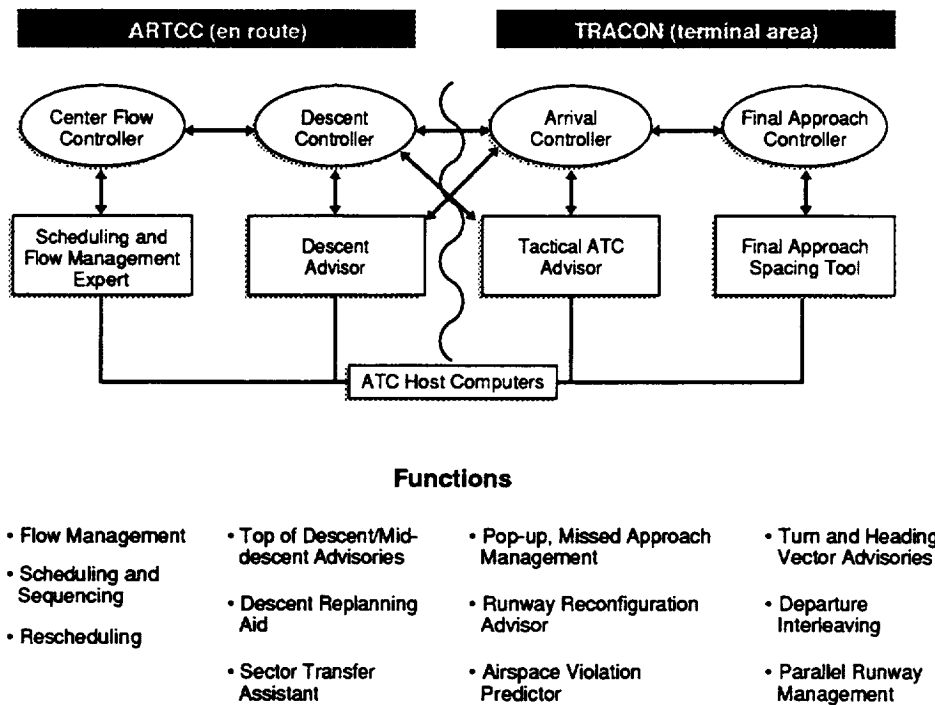
**Operational All-Weather Landing and Takeoff Systems.** As traffic density increases and use of the GPS becomes a reality, the need for maximizing airport runway availability will also increase. To simplify traffic management, aircraft designers must seek technologies that not only are properly integrated with other system elements but also provide capabilities for the airplane to continue operating in an autonomous fashion when faced with potentially dangerous environmental conditions.

### TECHNOLOGY NEEDED

Airborne navigational capabilities that integrate elements in such a way as to ensure optimal operational capability and overall system fault tolerance (e.g., airborne downlink data to aid in air traffic control surveillance and traffic management)

### NASA ROLE

V, TA (specifically for autoland as well as navigation)



Source: Boeing Commercial Airplane Group

FIGURE 10-2 Taxonomy of ATM automation aids.

### TECHNOLOGY NEEDED (cont'd)

### NASA ROLE (cont'd)

Precision runway guidance required to ensure that aircraft have the capability for autonomous operation as a backup to ground-based systems

SD&I, V, TA

Precision runway guidance sensors, integrated with on-board landing guidance system and data base of landing site information, to enable accurate synthetic vision displays

SD&I, V, TA

Integration of fuel optimization flight path with ATM metering system

R, SD&I, V, TA

Automatic aircraft flight path monitoring (on board) versus aircraft configuration for takeoff and landing

V, TA

**Communications**

**Automated Digital Data and Voice Communications to ATM System.** When used in conjunction with digitized high-speed communications technology, satellites offer a solution to many of the current problems encountered in today's flight path management. To realize the potential of these new and complex technologies, more attention to questions of proper integration is required. Aircraft manufacturers are preparing to take full advantage of the new technologies; however, modern aircraft already have operational capabilities that are not, or cannot be, realized fully in today's operating environment.

**TECHNOLOGY NEEDED****NASA ROLE**

Satellite communications uplink and downlink for interchange of ATM system data	V, TA
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Satellite communications downlink for on-board weather sensor (e.g., radar), video (i.e., wide bandwidth) data to support extended weather data advisory system	V, TA
-----------------------------------------------------------------------------------------------------------------------------------------------------------------	-------

Integrated very high frequency (VHF) radio communications and satellite communications with automatic link establishment transparent to crew	V, TA
----------------------------------------------------------------------------------------------------------------------------------------------	-------

Satellite communications and/or data link for transmission of in-flight diagnostics to ground-based maintenance facility	TA
--------------------------------------------------------------------------------------------------------------------------	----

Integrated antenna and radio frequency signal processing for radio-communications, satellite communications, GPS, distance-measuring equipment, and air traffic control transponder	TA
-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------	----

System integration	V
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**Collision Avoidance**

**Integrated Ground/Air-Based Collision Avoidance Systems with Appropriate On-board Situational Displays.** Collision avoidance will become a more critical issue if air traffic density increases as forecast. The technologies to deal with it are available now, but validation and systems integration are major concerns.

**TECHNOLOGY NEEDED****NASA ROLE**

Downlink to ATM system of Terminal Collision Avoidance Systems (TCAS)-detected threats and integration of these data with flight path management

SD&I, V, TA

Independent airborne resolution of traffic alerts, comparing onboard TCAS data with ground-based data link transmissions of potential threats

SD&I, V, TA

**Integrated Airport Ground Traffic Management.** A highly publicized, aircraft ground collision in Los Angeles in 1991 illustrates the need for improved situation awareness. Traffic and potential threat status must be available, in real time, to airborne and ground traffic as well as to the control tower.

**TECHNOLOGY NEEDED****NASA ROLE**

Integration of airport ground traffic control data by using surveillance radar and aircraft runway steering sensors

V, TA

Integration of onboard differential GPS/inertial position/velocity reports for ground traffic surveillance data and for automatic threat resolution

SD&I, V, TA

**Bad Weather Detection and Avoidance**

**Airborne and Ground-Based, Real-Time, Weather Threat Displays and Alerting Systems.** The promise of microwave landing systems, coupled with the forecast traffic increase, underlines the need for accurate detection and charting of weather threats to avoid excessive flight delays.

**TECHNOLOGY NEEDED****NASA ROLE**

Optical and Doppler radar sensors for clear-air turbulence detection

R, SD&I, V

Automatic downlink of severe weather and turbulence-detection graphical data, preprocessed onboard with detailed position coordinates

SD&I, V

Improved optical and radar detection of windshear and heavy rain, with quantitative threat estimation capability on board

R, SD&I, V

Integrated windshear detection and avoidance.

R, SD&I, V

### **Unique Rotorcraft Requirements**

**Automated Nap-of-the-Earth Guidance for Rotorcraft.** A leading cause of civil rotorcraft accidents is collisions with uncharted obstacles such as power lines. This is a major contributor to the fact that helicopters on emergency missions have high accident rates. The hazard potential of obstacles in nap-of-the-earth navigation increases significantly in low visibility and adverse weather conditions. Solutions lie in improved sensor technology and appropriate coupling of this information to aircraft flight controls and head-up displays.

#### **TECHNOLOGY NEEDED**

#### **NASA ROLE**

High-resolution obstacle detection sensors, including wire detection R, SD&I, V

Obstacle avoidance guidance R, SD&I, V

### **PILOT/VEHICLE INTERFACE**

Fundamental to increased safety in the commercial and military airspace of 2020 will be optimization of the pilot's situational awareness and spatial orientation. The Committee has identified simulation, cockpit display and control technologies, and synthetic vision/virtual reality as key to providing this capability. A truly integrated cockpit with intelligent automation is evolving, but significant steps must still be taken and many emerging technologies must be considered and exploited properly.

#### **Simulation**

Simulation has become recognized as an increasingly economic, effective, and safe means to design and validate systems. All simulations require validation in order to predict performance.

#### **TECHNOLOGY NEEDED**

#### **NASA ROLE**

Development of techniques and specifications to accelerate simulator validation R, SD&I, V

#### **Cockpit Display Technology**

Spatial orientation is enhanced through improvement in the display media used in the visual presentation of aircraft attitude and motion data. The traditional visual interpretations of spatial orientation are reinforced through the use of other human senses. Virtual auditory and

display systems will allow an "open cockpit" awareness of aircraft attitude; rates; normal/abnormal aircraft system operation; and relative orientation of other aircraft, the ground, and weather. There will be less reliance on voice communications in the ATM system.

<b><u>TECHNOLOGY NEEDED</u></b>	<b><u>NASA ROLE</u></b>
Wide field-of-view optics allowing single-panel panoramic instrument panels and synthetic vision windows	SD&I, V
Improved clarity of field of view of head-up display symbology through color, contrast, perspective, and enhanced effective optical focus at infinity, as well as use of the windscreen as the combining glass	SD&I, V
Helmet-mounted display hardware improvement allowing light weight, and full field of view	SD&I, V
Eye and head tracking technology	SD&I, V
Direct writing on the retina	R, SD&I, V
Virtual auditory systems that provide sound orientation to the airplane and the external environment	SD&I, V
Enhanced voice synthesis techniques with advances in computational rates and clarity	R, SD&I, V
Displays for nonaudio ATM system communications	R, SD&I, V
Techniques for enhancing display resolution and development of new display media	R, SD&I, V

### **Cockpit Control Technology**

The increased variety of methods for pilot control of aircraft cockpit functions will complement the development of display technology and will be made necessary by the accelerating complexity of the civilian and military environment.

**Voice Control.** Enhancements will allow the pilot to command and query the aircraft through structured sentences. Voice control will allow the pilot to transfer control of the aircraft to automated systems during incapacitating emergencies.

**TECHNOLOGY NEEDED****NASA ROLE**

Improved algorithms for voice recognition and parsing of words and syntax R, SD&I, V

Compensating techniques for variations in human speech (e.g., pilot/copilot) and for individual variations due to factors such as stress SD&I, V

**Hand Gesturing.** Control will be necessary for "virtual reality" systems, in which cockpit hardware is replaced by a visual representation. Motion of forearms, legs, will be used in military aircraft to supplement existing hand motion control.

**TECHNOLOGY NEEDED****NASA ROLE**

Development of reliable mechanisms for tracking body motions and flexure SD&I, V

**Design of Fiber-Optic Control Sticks, Transducers, and Switches.** Fiber optics complement all optical aircraft.

**TECHNOLOGY NEEDED****NASA ROLE**

Optical force transducers, toggles, and buttons requiring no electrical-to-optical conversion SD&I, V

**Unique Synthetic Vision/Virtual Reality Considerations**

Synthetic vision replaces, or augments, the cockpit windows by superimposing sensor data (television, infrared, microwave) on the normal visual scene. Virtual reality extends the synthetic vision concept further by synthesizing the entire cockpit and aircraft external environment through the combination of sensor data, previously stored data, and real-time data received through aircraft data links. Virtual reality technology means that the pilot's point of view need not be tied to the pilot's eye location.

**Replacing Cockpit Transparencies.** Aircraft sensor data will require enhanced capabilities from those sensors. Sensor suites not only will create a visual telepresence but will provide weather detection, clear-air turbulence detection, obstacle avoidance, wake vortex avoidance, and reduced vestibular and visual illusions due to cloud decks, window reflections, and ground lights. Head motion will be minimized by the fusion of all sensor data into one head-up or helmet-mounted display. Infrared and remote television sensors will allow the crew

to monitor the aircraft structure, wheel trucks, and proximity of the gear to taxiway edges and ground obstructions.

The level of on-board database-enhanced detail will be controllable by the crew, for example, high cultural detail for landing and ground operations. Details critical to safety (traffic, ground obstacles during low flight) would be basic at all times.

<u>TECHNOLOGY NEEDED</u>	<u>NASA ROLE</u>
Increased sensor resolution and sensitivity	R, SD&I, V
Development of sensor systems and combinations of sensors less prone to atmospheric or other interference	SD&I, V
Investigation of sensor placement on the aircraft structure; consideration of pilot's field of view, collocation of sensors, effects due to aircraft structure and surrounding air, conformal antenna placement, and electronic scanning	SD&I, V

## AVIONICS AND CONTROLS INTEGRATION

To enable many of the benefits promised by the introduction of digital electronics into avionics, advances are needed in hardware and software design techniques and performance evaluation methods. Introduction of new devices and components can improve performance and reduce cost; parallel processing can provide the computing power to take advantage of new capabilities; software design techniques can reduce software errors and improve performance; proper use of fault tolerance techniques can improve reliability and safety; and verification and validation methods can ensure that system designs meet their performance and reliability requirements and also improve the certification process.

### Hardware

**Photonics.** Photonics technology is needed to enable optically-based systems that will simplify testing and certification against high-intensity radiated fields and reduce the weight needed to shield electrical systems.

<u>TECHNOLOGY NEEDED</u>	<u>NASA ROLE</u>
Network configuration evaluation tools; testing methods	SD&I, V
Communication protocols; optical sensors; optical signal conditioning	SD&I, V



**Parallel Processing.** Although anticipated commercial avionics applications can be accommodated with a state-of-the-art single processor system, the fault tolerance required by flight-crucial systems adds substantial overhead that significantly reduces the effective throughput of avionics computers. Parallel processing is a promising technique to provide the necessary computing power to accommodate fault tolerance overhead.

**TECHNOLOGY NEEDED****NASA ROLE**

Network topologies; synchronization techniques

R, SD&amp;I

**Passive Cooling.** The use of smart sensors/actuators increases the presence of electronic components in locations where active cooling is inappropriate or infeasible.

**TECHNOLOGY NEEDED****NASA ROLE**Integrated electronic design/thermal management tools; SD&I, V  
high-temperature electronics

**Devices and Components.** Reduction in failure rate and increased reliability are needed.

**TECHNOLOGY NEEDED****NASA ROLE**Integrated failure rate estimation tools; high-temperature R, SD&I, V  
electronics; thermal environment analysis tools**Software**

**Computer-Aided Software Engineering.** Design and analysis tools that include requirements, design, code generation, documentation, analysis, test, configuration management, and operational support are needed to improve reliability in software development and ensure software integrity.

**TECHNOLOGY NEEDED****NASA ROLE**

Integrated design, analysis, and reuse tools

R

**Reuse Technology.** Software reuse can have a dramatic impact on development, testing, and reliability. A consistent approach to software reuse is needed to reduce cost, improve quality, and reduce development time.

**TECHNOLOGY NEEDED****NASA ROLE**

Cataloging, retrieval, and certification methods

R

**Parallel Processing.** Effective utilization of parallel machines demands major advances in recognition of parallelism in algorithms, partitioning schemes, compiler technology, and operating systems.

**TECHNOLOGY NEEDED****NASA ROLE**

Distributed operating systems; partitioning techniques

R

**Expert Systems.** Diagnostic, health, and status monitoring systems are required to reduce maintenance costs.

**TECHNOLOGY NEEDED****NASA ROLE**

Wider application of expert systems organized-domain knowledge; development of inference engines

SD&amp;I

**Data Compression.** The ability to handle large amounts of data with reasonable memory and interface systems is required.

**TECHNOLOGY NEEDED****NASA ROLE**

Data compression algorithms, including "wavelet" technology engines

R, SD&amp;I

**Neural Networks.** Pattern recognition of faults and faulty manufacturing actions in real time may be possible due to extremely high-speed computation and learning of neural networks.

**TECHNOLOGY NEEDED****NASA ROLE**

Theoretical basis; validation techniques

R

**Functionality**

**System and Software Reliability.** Design methods and software reliability techniques and analysis tools are needed to support design for testability and validation.

**TECHNOLOGY NEEDED****NASA ROLE**

Modeling techniques; software instrumentation; performance/reliability trade-off techniques; and techniques to estimate and increase mean time between failures

R

**Architecture**

**Fault Tolerance.** Schemes are needed for making trade-off analyses of different topologies for optimizing weight, power consumption, performance, maintenance costs, and reliability.

**TECHNOLOGY NEEDED****NASA ROLE**

Techniques for managing redundant computing resources; definition of fault classes

R

**Verification & Validation**

**Formal Methods.** Techniques are needed that use mathematical logic to demonstrate the consistency between specifications and implementation.

**TECHNOLOGY NEEDED****NASA ROLE**

User-friendly theorem provers; formal specification languages; mathematical verification methods

R, SD&amp;I

**Integrated Tool Set.** Design and assessment tools must be integrated to provide improved productivity in development of systems.

**TECHNOLOGY NEEDED****NASA ROLE**

User-friendly interfaces; interface parameter definition

R, SD&amp;I

**CONTROL FUNCTIONAL APPLICATION**

To increase the functional capability of the mechanisms by which aircraft flight is controlled, the Committee has identified controllability and maneuverability, load alleviation and ride control, engine control, aerodynamic flow control, and noise reduction as areas in which NASA must play a significant role. The following sections describe in detail how NASA research, development, and validation can play a part in bringing specific key technologies to fruition.

### **Controllability and Maneuverability**

**Relaxed Static Stability.** Relaxed static stability or static instability (in tandem with center-of-gravity control) allows maneuverability improvements and trim drag reductions. Stability is provided by the flight control system. Fuel consumption improvements on the order of 5 percent are expected for conventional subsonic transports. The additional flexibility in center-of-gravity location and even greater fuel burn reduction are particularly important to tailless flying wing designs, allowing the use of more wing volume. Relaxed static stability will also significantly enhance subsonic performance of supersonic aircraft, which exhibit different inherent pitch stability characteristics in subsonic and supersonic flight. The major issues to be resolved are the provision of these functions at the needed levels of reliability.

#### **TECHNOLOGY NEEDED**

#### **NASA ROLE**

Adaptive fault detection, isolation, and reconfiguration techniques, and architectures to accommodate sensor, actuator, structure, surface, and processor failures or damage R, SD&I

**Integrated Controls.** Integration of flight and propulsion control systems enhances the optimization of steady-state and transient performance. Integrated control may be used to reduce fuel burn and extend structural life, reduce pilot work load, and improve accident avoidance capability by "closing the loop" around aircraft performance with coordinated control inputs; it can also enhance safety and reliability through reconfiguration following damage or failures. This is important in advanced subsonic aircraft, especially rotorcraft and tiltrotors. Emphasis needs to be placed on practical methods, because the gap between theoretical approaches and application has been too large in the past.

#### **TECHNOLOGY NEEDED**

#### **NASA ROLE**

Robust control design methods for multi-input/output with broad tolerance of system uncertainty R, SD&I

Adaptive fault detection, isolation, and reconfiguration techniques and architectures to accommodate sensor, actuator, structure, surface, and processor failures or damage R, SD&I

Adaptive control design methods for real-time application R, SD&I, V

Real-time multivariable system optimization techniques R

Control law partitioning methods for decentralized architectures R

Integration of lift/flow, maneuvering, and stability control with load alleviation through adaptive filtering and very wide bandpass actuation R

### **Load Alleviation and Ride Control**

**Active Flight Controls.** Alleviation of loads and rigid body and structural mode excitations (resulting from turbulence, gusts, maneuvers, buffeting, and flutter) with active flight controls allows the use of lighter structures and higher aspect ratios or more highly swept wings. Control surfaces are deflected to reduce aircraft response to atmospheric disturbances, redistribute lift to reduce critical structural loading, or damp wing and body structural modes. Aerodynamic flow control (described subsequently) is another method of achieving the desired distribution control forces and moments. Improved handling qualities, extended fatigue life, and improved ride quality and secondary loading are direct benefits. Applications to both advanced subsonic aircraft and rotorcraft must be addressed.

#### **TECHNOLOGY NEEDED**

#### **NASA ROLE**

Improved nonlinear computational fluid dynamics models of unsteady aerodynamic forces and aeroelastic interactions R

Intelligent structures providing local sensing of load, acceleration, and damage conditions, and distributed actuation for aerodynamic performance optimization and load alleviation R, SD&I, V

### **Engine Control**

**Active Inlet Distortion Control.** Active control of individual inlet guide vanes, based on measurement of local pressure distribution, could dynamically adjust compressor distortion tolerance. A design stall margin of 10–20 percent is possible.

#### **TECHNOLOGY NEEDED**

#### **NASA ROLE**

High-frequency sensors and actuators

SD&I

Control laws

R

**Active Combustion Control.** Low nitrogen oxide ( $\text{NO}_x$ ) burners required by High-Speed Civil Transport (HSCT) could exhibit combustion instabilities in the form of blowout. Active control techniques that sense the presence of burning via noise measurement might allow achievement of low emissions via high-frequency fuel flow modulation. Similar techniques may be used to eliminate afterburner screech and rumble.

<u>TECHNOLOGY NEEDED</u>	<u>NASA ROLE</u>
High-frequency, reliable fuel-metering actuators	SD&I
High-frequency, dynamic pressure sensors capable of measuring burner pressure fluctuations	SD&I
Control laws	R

**Active Compressor Surge and Rotating Stall Control.** Active control can be used to reduce or eliminate the design constraints and performance penalties imposed by compressor surge and stall. Some of the benefits that might be expected from active compressor stabilization are the potential for shorter, lighter engines; increased fuel efficiency; and simple inlets.

<u>TECHNOLOGY NEEDED</u>	<u>NASA ROLE</u>
High-frequency sensors and actuators with associated signal processing	SD&I
Rotating stall detection and suppression with associated signal processing	R

**Active Turbine Clearance Control.** Active control of turbine blade tip clearance based on real-time measurements of blade clearances, rather than open-loop scheduling would allow engine running with tightest practical clearances in the compressor and turbine, achieving the maximum available efficiency.

<u>TECHNOLOGY NEEDED</u>	<u>NASA ROLE</u>
High-temperature, reliable clearance control measurement	SD&I
Control laws that would preclude rub	R

**Magnetic Bearings.** Magnetic suspension bearings, in which the rolling contact is replaced by magnetic suspension of the rotating assembly, could use feedback control to maintain positional stability. In fact, this feedback can be used to control shaft dynamics. This would reduce engine maintenance, because vibrational coupling to the airframe often dictates engine removal before the engine itself demands it. Magnetic bearings might also permit removal of the oil systems—a tremendous practical advance.

**TECHNOLOGY NEEDED****NASA ROLE**

High-power electronics and magnetics in the hostile engine environment SD&I

Control algorithms for center-of-mass rotation, gyroscopic maneuver, and gust loads that preclude bearing rubbing R

**Aerodynamic Flow Control**

**Laminar Flow Control.** Boundary-layer control on wing, nacelle, and tail surfaces can be used to maintain laminar flow across the wing, drastically reducing skin friction. Laminar flow is maintained by sucking air out of the boundary layer through slots or perforations in the wing surface. Total aircraft drag reductions on the order of 20 percent are possible with extensive use of laminar flow control. The application may differ between cruise and climb/descent operations.

**TECHNOLOGY NEEDED****NASA ROLE**

Intelligent structures capable of detecting laminar/turbulent transition location, and of detecting and canceling incoming boundary-layer disturbances R, SD&I

Manufacturable/maintainable suction system, including surface perforations and distributed suction SD&I, V

**Variable Wing Camber.** A variable wing camber allows in-flight adaptation of wing geometry to local ambient conditions and maneuvering requirements. Chordwise pressure profile control via variable camber allows wing performance (lift/drag) optimization, whereas spanwise lift distribution control can be used to reduce wing bending stresses during maneuvering.

**TECHNOLOGY NEEDED****NASA ROLE**

Continuous variable camber wing SD&I, V

Intelligent wing structures sensing local load, pressure, and acceleration R, SD&I

**Noise Reduction**

**Active Noise Control.** Reduction of noise—both near-field (cabin) and far-field (community) noise—is possible through the use of active noise control. Antinoise concepts

adjust the output of single or distributed secondary acoustic or vibration sources (based on input from direct measurements of the acoustic field or the use of coherent measurements) to achieve destructive interference and noise attenuation. This technique is particularly useful at low frequencies where passive acoustic treatments are generally ineffective. Rotorcraft far-field noise, as well as local vibration levels, can also be reduced by active control of rotor pitch. Benefits of active noise and vibration control include reduced weight of passive airframe and engine acoustic treatments, and improved engine performance due to relaxation of design constraints to reduce noise levels. Both acoustic and structural actuation methods need to be considered.

### **TECHNOLOGY NEEDED**

### **NASA ROLE**

Durable, high-power, compact, efficient acoustic sources and drivers	R, SD&I
Fast, adaptive control algorithms for broadband and random noise cancellation with an uncertain plant and complex noise field	R
Improved numerical and analytical models characterizing noise propagation and structural/acoustic coupling for control, detection, and secondary source design	R
Control techniques for minimizing radiated three-dimensional noise fields	R
Individual rotor blade control systems to achieve higher harmonic control for vibration and noise reduction	R, SD&I, V

## **AIRCRAFT POWER AND ACTUATION**

The Committee believes that development of new and more efficient techniques for generating, storing, and distributing power would find great application in future aircraft systems, as well as in other areas such as automobiles and spacecraft. Thus, NASA is encouraged to aggressively pursue the elimination of complex secondary power systems on aircraft and to develop and validate simpler, more reliable actuation systems.

### **Power Sources**

**New Secondary Power Supplies.** Power for the hydraulic, electrical, and air systems currently comes from the main engine. These systems extract horsepower and penalize engine fuel consumption on the order of 3 percent directly, while adding complexity to engine systems with attendant penalties in fuel efficiency. This added complexity occurs in a hostile



environment and degrades the reliability of the aircraft's essential power source for flight. New secondary power sources can reduce the shaft horsepower extraction from the engines and result in a 1 percent savings in specific fuel consumption.

### **TECHNOLOGY NEEDED**

### **NASA ROLE**

Develop battery and fuel cell technologies for reliable, airborne applications R, SD&I, V

Develop cogeneration concepts, such as turbines, driven by cabin exhaust air or wingtip vortices R, SD&I, V

Application of high-temperature superconductivity as appropriate SD&I, V

Power-by-light concepts to take advantage of fiber optics R, SD&I, V

### **Actuation**

**New Actuators.** The current control surface actuation is accomplished by hydraulic actuators fed by a series of hydraulic lines coming from fluid reservoirs and powered by hydraulic pumps that are driven by the main engines. On a typical twin engine this transport system weighs approximately 2,500 pounds. These systems are also a leading cause of commercial aircraft dispatch delay because of their mechanical complexity and consequent low reliability.

### **TECHNOLOGY NEEDED**

### **NASA ROLE**

Electrohydrostatic actuator—a local hydraulic system that would reduce cost and improve maintainability R, SD&I, V

Electromechanical actuator—an electric motor with reduction gears that would improve reliability R, SD&I, V

Micromachine applications SD&I, V

**Supersonic Aircraft Actuators.** Supersonic aircraft have very limited space for actuators. Higher-pressure systems in military use are available, but other concepts are needed to avoid the surface fairing that would encompass large actuators.

**TECHNOLOGY NEEDED****NASA ROLE**

Develop hinge line actuation concepts

TA

## COGNITIVE ENGINEERING

### INTRODUCTION

For the next two to three decades the information sciences and human factors disciplines must play a different and more fundamental role in aeronautics than in the past, if aeronautical technology as a whole is to be advanced. Great improvements in vehicle characteristics and performance may be possible, but they cannot be realized effectively without accommodating major bottlenecks in system capacity, safety, and operations. To make these accommodations and improvements, information sciences and human factors will play central and enabling roles: information sciences to permit expanded capacity with safe operations and human factors considerations to achieve a well-balanced and highly integrated transportation system.

In the context of this study, the term "information sciences" includes the methods and systems for acquiring, storing, retrieving, distributing, checking and cross-checking, validating, transmitting, and displaying information needed in the operations of aircraft. It includes information used on board the aircraft as well as external to the aircraft, such as air traffic management (ATM) information.

The term "human factors" is used here to characterize human attributes and behavior as they relate to all facets of the ATM system. These include decision making, control, monitoring, strategic and tactical planning, and supervisory or other such behaviors as they interact with the vehicle and all elements of the ATM system. The emphasis is interactive and interdisciplinary; the goals are to optimize performance and safety in all elements of the overall ATM system.

The interdisciplinary activities associated with information sciences and human factors seem to demand an approach that is related to how people perceive data, convert these data to integrated information, and use this information as a basis for making a decision. Indeed as the power of computers is increased, a logical next step is to allow air crews to do what people do best and allow the computer to support these activities and carry out whatever other tasks are necessary. (In a sense, this is the inverse of the current approach.) This human-centered activity is a potential application of cognitive science to practical problems. Such human-centered activity involving multidisciplinary engineering activities and cognitive science is

### Recommendations

#### General

NASA should conduct broad-based, interdisciplinary research into the causes, nature, and alleviation of human error, with specific reference to airborne and ATM environments.

- The most promising theories and experiments should be pursued as part of a continuing, long-range effort aimed at accident reduction.
- NASA should lead in the development and validation of training and operational strategy and tactics that are intrinsically tolerant to situations demanding divided attention operations by the individual or crew.
- NASA should work with FAA and industry to address the total human/system concepts and develop methods to ensure valid and reliable system operations.

#### Specific

1. NASA should conduct research to develop and demonstrate techniques to improve the pilot's situational awareness and spatial orientation.
2. In addition to its work with the National Incident Reporting System, NASA should work with the FAA and the National Transportation Safety Board to analyze all available data on aircraft accidents and incidents to determine the history and trend of human errors, contributing factors, type of equipment involved, and other relevant matters.
3. NASA's research in error alleviation should include:
  - systems that can detect developing critical situations, independent of the crews' alertness, and inform and assist the crew regarding appropriate corrective measures;
  - concepts, methods, criteria, and the technology for error-tolerant system design; and
  - development of prototype, "massively smart" interfaces, both in the simulator and in the air.
4. NASA, with FAA involvement, should extend its investigations of highly reliable avionics to total system concepts applicable to ATM automation.
5. NASA should continue its research into four-dimensional guidance algorithms and simulation techniques for ATM.

denoted by the term "cognitive engineering." That term is used throughout this chapter to express the synergy between the traditional disciplines of information science and human factors.

The treatment of cognitive engineering is divided between this chapter and that on Avionics and controls (Chapter 10). For the most part, Chapter 10 covers the airborne systems and equipment that implement the on-board information and human factors requirements. This

**Benefits of Research and Technology Development in Cognitive Engineering****Enhanced Air Traffic Management System Performance**

- Effective information management
- Enhanced communication
- Greater situational awareness
- Integrated global system

**Enhanced Safety**

- Error avoidance and alleviation
  - Greater understanding of interactions between humans and automated systems
  - Greater understanding of human error
  - Error-tolerant design
- More effective training and skill maintenance

**Aircraft and Engine Design and Development**

- Integrated systems
- Technology validation

chapter treats those aspects that deal primarily with interactions between humans and machines. These include the content and format of information that allows crew members to interact with each other and with the on-board automation, ATM personnel, and ATM automation; the transfer of information between crews and the ATM system; and information required within the ATM system.

There are two overriding, interwoven themes in this treatment. Expressed as key challenges, they are: (1) the improvement of overall ATM performance, and the enhancement of safety.

That the first challenge exists is obvious to even the most naive user of the existing ATM. The technical answers to performance and capacity improvements are the introduction of advanced new aircraft, equipment, and facilities into the transportation system.

The second challenge may not be so obvious, because the existing ATM is one of the safest ways ever developed for point-to-point travel. The introduction of advanced avionics, glass cockpits, new training procedures, and more reliable systems and subsystems in aircraft since the beginning of the wide-body jet era has probably played a part in establishing the current downward trend of total accidents in the United States. There are insufficient statistical accident data since the introduction of the newest transport aircraft (MD-11, 757, 767, 747-400, A320) to fully evaluate the safety improvements achieved with application of advanced technology and the existing human factors guidelines. It is clear that the traveling public will insist on maintaining a high safety record (as measured by absolute number of accidents, not rate

of accidents) as the number of passenger-miles flown each year doubles, at least, over the next few decades. Historically, human error has been cited as the cause of 70 percent of aircraft accidents. This percentage has been remarkably resistant to major advances in aeronautical technology and seems to border on a universal constant. Near accidents and incidents are increasing, and expanded operations increase the exposure and the risk. In the final analysis, safety will continue to depend on the human elements in the overall system, which starts with preliminary conception and continues through operations. Consequently, human error as the cause of a great majority of accidents is unacceptable for an expanded and enhanced ATM and must be reduced.

This chapter discusses the Committee's findings and recommendations regarding the future of cognitive engineering as it relates to the field of aeronautics. The boxed material summarizes the primary recommendations that appear throughout the chapter, with specific recommendations given in order of priority, and the benefits that can be gained through greater research and development in cognitive engineering.

## **VISIONS FOR 2020 — PRECEDENTS AND CONTEXT FOR RESEARCH ACTION**

This report attempts to look ahead two to three decades. Details of the then-existing air transportation system are somewhat obscure. As an attempt to pierce this veil to discern the key challenges faced by human factors and the information sciences, the approach taken here begins with an outline of some tentative "visions" or goals for 2020. These "strawman" concepts have been selected to serve as goals on which to orient, structure, and/or inspire the establishment of research needs. The strawmen are broadly based, with indefinite time scales; thus, the actual satisfaction of research needs may have parallel flexible time scales. The visions are in three broad categories:

1. Those desirable systems, features, and characteristics that are assumed by the Committee to be present in 2020: these must precede or be concurrent with vehicle developments, which in one degree or another rely on them.
2. ATM systems—two extremes:
  - a centralized, ground-based ATM system based on evolution from the National Airspace System;
  - a distributed, combined, space- and ground-based ATM. This global, cooperative system would provide optimal operational capability, surveillance, blunder detection, automated digital data and voice communication, collision avoidance, and conflict potential, via centralized computing facilities. Position measurements for all flight operations (including autoland and ground movements) would be derived from the Global Positioning System (GPS) or its 2020 equivalent.

3. Supervisory telerobotic human/machine systems: these cover a broad spectrum of adaptive-role human/machine systems, the most elaborate being hybrid-synergistic human/automation systems with dual-role bilateral operations. That is, the system performs operations, surveillance, monitoring, and backup with either the human or the automation as primary in a given role (with the other element then in backup). 2020 examples of this type of system might include: pilot/co-pilot/cockpit automation; ATM, space, and terrestrial operations of all sorts (proximate or remote).

It is expected that these advanced systems will be based on a clearly stated "human-centered" automation philosophy,<sup>1,2</sup> and that they will have agents to manage information, to manage tasks, and to monitor and remediate errors. In other words, the system will be designed to allow people to do what they do best, with machines playing a supplemental role.

### **Aeronautical Vehicle Visions for 2020**

In discussions of vehicle possibilities, some assumptions have been made about the availability of certain human- or automation-oriented equipment, facilities, or capabilities in the early twenty-first century. One role of cognitive engineering in this era is to enable these assumptions to become reality. Some assumptions are implicit, such as equivalent safety of operations, whereas others are explicit. The latter are mentioned in several places throughout the vehicle sections. These include: integrated satellite/on-board systems permitting:

- on-board en route navigation and position fixing;
- elimination of separate Terminal Collision Avoidance System (TCAS);
- routine Category IIIc operations — elimination of microwave landing systems (MLSs) and instrument landing systems, and very high frequency (VHF) omnidirectional range approaches; and
- fully integrated cockpit and ATM system.

Information sciences is an enabling discipline for all of these advanced systems. The following are among the implications for human/machine interface systems:

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<sup>1</sup> Billings, C.E. 1991. Human-Centered Aircraft Automation: A Concept and Guidelines (NASA Technical Memorandum, No. 103885). Washington, D.C.: National Aeronautics and Space Administration.

<sup>2</sup> Rouse, W.B, N.D. Geddes, and R.E. Curry. 1987. An Architecture for intelligent interfaces: Outline of an approach to supporting operators of complex systems. Human Computer Interaction 3:87-122.

- no manual reversion;
- displays and sensors: (1) for situation awareness, and (2) nonmoving sidearm controller (as a reduced awareness "display" for both the "pilot flying" and the "pilot not flying;")
- operational aspects of glass cockpit airplanes, such as: (1) tunneling attention and action, to the exclusion of other crew functions, and struggling with the automatic controls command settings "to make the airplane do something it clearly doesn't want to do," instead of disengaging and manually flying to the desired condition;
- overreliance on automation in nonnormal situations;
- transitions from one flight phase to another, from one control mode to another, from normal to abnormal situations; and
- enhanced surveillance systems.

These advanced systems to support advanced vehicles may also bring an additional legacy of awkward human factors problems, for example

- a tendency toward crew complacency and overreliance on automation;
- boredom/fatigue;
- a greater need for discipline and orderly joint sequences as automation increases;
- several different, nonstandard, cockpit automation systems in a given airline fleet;
- shorter times between new equipment generations, with more frequent shakedown of new systems and needed crew transitions due to rapid changes in the technologies and the equipment production base; and
- potential for additional workrelated stress due to systems demands, capacities, and economic impacts (e.g., "go" pressure).

### **Air Transportation System Visions for 2020**

Two versions of potential operational environments that might exist in 2020 are defined as the bases for identifying required research and development and innovative concepts in cognitive engineering. The first is an extrapolation of the evolving Federal Aviation Administration (FAA) ATM system and the corresponding extrapolation of aircraft/systems technology. This scenario is based on a paper describing the FAA view of the ATM in the twenty-first century.<sup>3</sup> The system is referred to here as the "evolutionary" system. The challenges in cognitive engineering for this system also tend to be evolutionary, albeit not trivial. There have been major programmatic responses to the emerging requirements of this evolutionary ATM system, containing both airborne and ground-based constituents. The

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<sup>3</sup> U.S. Department of Transportation. 1990. Moving America into the 21st Century — FAA Strategic Plan.



National Aeronautics and Space Administration (NASA) Aviation Safety Automation Program is ongoing, and the National Plan for Aerospace Human Factors<sup>4</sup> is in its initial stages.

The second potential operational environment is a visionary projection of what might be possible from a technical viewpoint that ignores, for the moment, implementation issues. This "visionary" ATM system is intended to motivate innovative thinking and creative ideas that are more advanced than those needed for the evolutionary ATM system. Table 11-1 outlines the key features of the two scenarios.

It is important to note that the visionary scenario portrays the technical possibility of fully automatic aircraft operations, with the ATM system providing the primary means of operating and managing most air traffic flow from gate to gate. This could imply the total removal of humans from the cockpit and ATM control rooms. Indeed, it would, in principle, reduce on-site human involvement and the direct attribution of human error to crew. It would also have economic consequences that could be favorable to direct operating costs. However, a fundamental problem is we do not have historical data on how many accidents have been prevented by human presence and intervention that would not have been prevented by an automatic system. Although it would be virtually impossible to establish such a data base, the capacity of humans to recognize and correct things that have gone awry is an enormously valuable and uniquely human attribute. In fact, with a human-centered automation philosophy the pilot will be in ultimate charge because (1) this is the natural preference of flight and operating personnel, for many reasons, including poor or unpredictable performance of automation; (2) pilots must have authority if they are responsible for safe flight operations; and (3) experience to date strongly suggests that better performance of the total human/automation system will occur if humans are in charge.

The Committee believes that the closest full automation likely by 2020 involves a scenario in which the primary operational mode for most aircraft and the ATM is automatic, with humans actively engaged in higher-level (strategic) decision making, supervising and monitoring operations, and taking direct control if necessary. The crew and ATM monitors would have automated tools to aid them in supervision, monitoring, and control takeover. There would also be automatic surveillance—independent systems to monitor the normal automated system and/or human actions when humans are in control. These monitoring systems would advise humans when their actions appear to be inappropriate, based on understood intentions and a projection of consequences.

### **Supervisory Telerobotic Human/Machine Systems Visions for 2020**

The last type of strawman system to serve as a possible focus for cognitive engineering needs is the most elaborate and multifunctional. It includes aiding, control, monitoring,

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<sup>4</sup> U.S. Department of Transportation. 1990. The National Plan for Aviation Human Factors. Volumes I and II (draft). Washington, D.C.: Federal Aviation Administration.

TABLE 11-1 Key Features of Two Scenarios for the Air Transportation System in 2020

	Evolutionary	Visionary
Operating environment	Operating environment information (OEI) from ground-derived sources augmented with aircraft data (i.e., winds aloft, windshears, severe weather, runway conditions, and wake vortices). Doppler radar at major airports. Real-time weather observations from aircraft, air data sensors, inertial navigation system (INS), and windshear sensors transmitted to ground stations and integrated with ground-derived observations. Sophisticated weather models to provide weather predictions in a timely manner to the aviation community.	OEI from integrated sources using space sensors, ground sensors, and aircraft data. Real-time updates provided to all aircraft via data links for their route and alternates if requested. OEI data to include those listed to the left plus short-term weather forecasts along planned route, including icing conditions for GA and helicopters.  Real-time data and short-term predictions of landing conditions, including vortex wakes, windshears, severe turbulence, thundershowers, and microbursts displayed to crew and to ground monitors.
Aircraft position, surveillance, and maneuver intentions	Altitude reporting secondary surveillance radar transponder augmented by Global Navigational Satellite System (GNSS) is (possibly) the basic source of aircraft positions. Ground-based surveillance using secondary radar. Primary radar to detect aircraft blundering into terminal control areas as backup to secondary radars. Surveillance over ocean and in low-density en route airspace to be by satellite-based Automated Dependent Surveillance (ADS) using on-board navigation system data linked to ground station via satellite. Airport surface position via radar augmented by SSR Mode S multilateration or GNSS.	GNSS augmented by INS is the primary aircraft position system. Data link aircraft-derived state vector to ATM center for position and maneuver intentions. Altitude-reporting SSR transponder for backup and minimum-equipped aircraft. Satellite-based ADS using GNSS and data linked to ground station via satellite for global surveillance.  GNSS augmented with ground-based sensors for airport surface position.
Procedures, separation standards, and collision avoidance	Use of cockpit display of traffic information (CDTI) and crew involvement in separation standards for aircraft with more accurate and reliable guidance systems. TCAS to provide backup separation assurance to the ground-based ATM system. CDTI used for in-trail station keeping on arrival and separation monitoring on departure to operate at lower minima. Flight crews to resolve local separation problems en route (low-density situations) and over oceans with CDTI.	Use CDTI for crew monitoring automated aircraft separation in addition to ground monitoring. Accurate prediction of vortex wakes allows minimum separation at landing to be set by aircraft ground-handling capacity and allowances for anomalies. Collision avoidance integrated into the automatic ATM plus independent on-board system integrated into CDTI as monitor and backup to automatic ground/data link system. CDTI used to monitor ground traffic while taxiing.

	Evolutionary	Visionary
Traffic flow, information, and ATM automation	<p>Real-time flow management automation tools to offer flow strategies to adapt for traffic, terminal area, and airport conditions. Shared flow strategy decision making between aircraft crew and ground-based ATM. Short-term prediction of airport capacity. Tight integration of the central flow management process.</p> <p>User to negotiate best trajectories with ATM system. Tactical management system monitors aircraft progress and intervenes only when necessary to meet ATM constraints. Negotiations are between aircraft flight management system and ground ATM system. Flight crews and ATM managers are kept informed so they can intervene if necessary. Will use four-dimensional clearances. Ground air traffic managers to integrate aircraft not equipped with four-dimensional flight management systems.</p>	<p>Automatic four-dimensional management for gate to gate as normal procedure for most aircraft. Exception to flow management for older and GA aircraft without four-dimensional systems and off-nominal operations of other aircraft. Automation tools for integrating four-dimensional and non-four-dimensional aircraft. Tight integration of the central flow management process. Computer-generated clearances issued to aircraft via data link. Controller monitors operation and intervenes selectively. Automated ATM will include the ground segments to allow for positive control from gate to gate. Special-use airspace and ATM procedures to enable advanced rotorcraft operations separate from normal traffic at major hubs.</p> <p>Continuous 24-hour prediction of airport capacity.</p>
Navigation, guidance, takeoff and landing	<p>Primary terminal, en route, and oceanic navigation by GNSS. Category I approach and landing aids by GNSS together with ground-based aids (i.e., differential GPS). Category III provided by MLS.</p>	<p>Primary terminal, en route, and oceanic navigation landing and ground control to be GNSS augmented with INS and ground aids for Category IIIc. Automatic takeoff and ground operations (from and to gate) possible. Use of synthetic vision/enhanced vision systems for monitoring Category III landings and ground operations.</p>
Communications	<p>HF communication in polar regions. VHF voice and data communications continue to be used. Satellite communications to be used over oceans and some land areas.</p> <p>Extensive use of data links between ground and flight deck. Open system interconnection (OSI) incorporated to ensure interoperability of satellite, Mode S, VHF, and terrestrial data transmission systems.</p>	<p>UHF satellite communications for all voice and data communications.</p>

supervisory, and surveillance aspects.

Examples of the aiding elements follow from the visionary ATM described above. These include automated tools that aid the humans in supervisory, monitoring, and control roles; advisors of inappropriate actions; and projection of consequences. To enable these tools to operate most effectively, they must be based on an understanding of how humans perceive and process information. Current concepts include using advanced computer and software systems to serve as "associates" for pilot and air traffic control personnel.

Other features follow from current human/vehicle control systems, such as automatic flight management, guidance, and control systems. At the simplest level this is a pilot-controlled "effective vehicle," in which the effective aircraft comprises the airplane plus stability and command augmentation system. The stability and command augmentation system (SCAS) corrects any dynamic deficiencies of the bare airplane. Flight management and guidance for manual operation are accommodated with displays such as flight directors, which, in company with the SCAS, create an effective vehicle that handles well and possesses "good" flying qualities for all operational modes. At the next level is automatic flight control, in which the pilot is removed from direct flying operations but still makes command decisions, exerts control of flight modes, inserts commands, and monitors operations. Some of the monitoring cues are provided by the same displays used in manual control, whereas other monitoring cues stem from the aircraft's behavior in response to commands and disturbances. These are also "flying qualities," albeit those for intermittent or unattended operation by the pilot. Finally, there is completely automatic flight management, guidance, and control, in which the autopilot is coupled to flight management systems without human intervention, but with human initiation and monitoring.

The final feature is automatic surveillance (i.e., independent systems to monitor the normal automated system or human actions when humans are in control). Monitoring operations in general are those associated with ensuring that any abnormal situations are properly detected and identified; the additional dimension of surveillance is independence, even detachment, of the oversight. This is essential for the detection of "blunders," which typically occur when individual operations are apparently proceeding properly but the total picture is one of incipient catastrophe.

A major distinction between monitoring and control tasks is that pilots and automation may perform the same monitoring task simultaneously (in parallel), whereas control tasks are performed by either the crew or the automation. One result of this dichotomy is that there is no upper limit to the automation of monitoring tasks since they will not interfere with the pilot if they are well implemented. Therein lies a major challenge.

From the information sciences standpoint these human/automation systems will contain at least three major components:

1. interface manager—provides flow of information to the pilot and crew in a form that allows for most effective use; preserves priorities and maximizes effective flow via message scheduling and formatting;

2. error monitor/identifier—logic to monitor for errors, to identify and evaluate the impact of errors including systems to infer the pilot's intent; and
3. task manager—"chief of staff"—sets priorities sensitive to the intent of the executive, determines what gets through, and responds to orders.

Several supporting elements are critical to the success of an advanced human/automation system. These include the "pilot intent inferencing system" noted above with the error monitor/identifier; a "pilot model of capabilities/resources/limitations," and a "world/system model." These elements support error evaluation (i.e., using the world/system and capabilities/resources/limitations models).

The supervisory telerobotic human/machine systems envisioned here thus include all the features exemplified above combined into a hybrid-synergistic human/automation system with dual-role, adaptive bilateral operations. That is, the system performs operations, surveillance, monitoring, and backup with either the human or the automation as primary in a given role (with the other element as backup). Some 2020 examples of this type of system might include pilot/copilot/cockpit automation; and ATM, space, and terrestrial operations of all sorts (proximate or remote).

## TO MAKE GOOD THE VISIONS

What stands in the way of the execution of such visions? The primary technical factors include

- effective human/automation interactions for airborne and ground-based systems/operations;
- design, development, invention as needed, execution, and validation of sufficiently reliable systems of hardware and software;
- effective management and distribution of the necessary information to active, passive standby, and monitoring nodes;
- validation that the systems would substantially increase capacity and overall performance/safety; and
- implementation plans and procedures that meld the new features into the existing system without disruption.

The last factor is particularly difficult because of the enormous technical, political, and economic complexity of the existing ATM. An evolutionary approach is needed for each new step introduced. Thus, even if the system is ultimately to evolve to full automation, it would go through a series of stages, with humans retaining partial control to develop sufficient confidence to move to the next level of automation.

## THE CHALLENGES

Although the strawman systems described range from evolutionary to revolutionary, they represent a broad spectrum of system possibilities that could make major contributions to the improvement of overall ATM performance in terms of capacity and operations, with simultaneous enhancement of safety. Although the several strawman systems may have different impacts and time scales, they motivate and demand similar cognitive engineering research and development advances. Using the exemplary systems and visions as guides, the Committee has converted the needed advances into broad challenges.

The primary challenges for cognitive engineering research and development in aeronautics over the next two to three decades are to (1) establish the most effective human/automation interactions; (2) ensure valid and reliable systems operations; and (3) provide highly effective management and distribution of information. Each of these challenges relates to the entire air transportation system including all types and mixes of aircraft; air traffic management; all types of information acquisition, processing, and distribution systems; and all associated processing, procedures, training, monitoring, checking, and surveillance activities.

The challenges are discussed below in terms of major research categories:

- safety enhancement in the air transportation system,
- assurance of valid and reliable systems operations, and
- effective management and distribution of information.

## SAFETY ENHANCEMENT IN THE AIR TRANSPORTATION SYSTEM

A thorough and comprehensive understanding of human/automation system dynamic interactions is at the heart of enhanced safety in future aeronautical systems. At the broadest level, the achievement of effective human/automation interactions demands a reduction in error potential, the means to recognize and reduce error once it occurs, and techniques to enhance error-free performance. **An important continuing first step is for NASA to analyze all available data on aircraft accidents and incidents to determine the history and trend of human errors, the contributing factors, the type of equipment involved, and other relevant matters.** The Aviation Safety Reporting System (ASRS) administered by the NASA Ames Research Center is an excellent source for such information. The human error analysis reports should be transmitted to those responsible for developing systems, improving procedures, and training for immediate use, and should be used as a guide to focus human factors research on the most important payoff areas. The goal in this challenge is to gain the knowledge and develop methodologies and tools to design systems and procedures that minimize errors and their effects on aviation safety. To achieve these goals requires broadly based research and technology efforts treating (1) human error theories for aeronautical applications, (2) human and systems performance measurement for assessment of human error potential, and (3) alleviation of error—error-tolerant systems.

## **Human Error Theories for Aeronautical Applications**

### **General**

The human errors of primary interest occur in a human/machine system context in which errors result from interactions that are themselves, or can lead to, undesirable dynamic consequences (errors). The operations of the human/automation system are such as to achieve well-defined purposes and goals, and the errors are connected with unacceptable deviations from desired progressions to achieve a purpose or goal.

Adequate theories of human error in manned aircraft are difficult to develop because (1) the overall systems are extremely complex and interdisciplinary in character, (2) the understanding of the behavior of human elements is not as advanced as that for automation components, and (3) accidents/incidents are very low-probability events, often leaving incomplete information as to possible sequences and causes.

The descriptive schemes and abstractions needed to characterize human/vehicle interactions must reflect the dynamic attributes of behavior in the human and automation components. It follows directly that any theory likely to be useful in shedding light on human error in the aeronautical milieu must have a common descriptive framework (e.g., common forms of mathematical models for description of the physical technological/engineering components and human behavioral components). If the systems were totally automatic, the appropriate theoretical constructs would be those of vehicular control and systems engineering, comprising deterministic and stochastic aspects, with a dynamic reliability flavor. The substitution of human components introduces a great deal of complication because human control behavior can be much richer than the automatic variety; because human cognitive behavior enters the scene; and because human variability as functions of task, environmental, and operator-centered variables introduces dimensions that are not present in an automatic system. To meld such features into useful theories clearly requires highly talented, integrated partnerships of dynamic systems engineering and behavioral science (i.e., cognitive engineering). Entities both inside and outside NASA have important contributions to make; joint efforts and collaborations are essential to achieve a critical mass of talent and technical/scientific resources.

### **Criteria for Useful Theories of Human Error in Aviation**

To be useful in design, prediction, and assessment—or even for insight—theories of human error should satisfy certain criteria. In general, they should be (1) descriptive modifications of operational experience/data; (2) predictive, at least in a probabilistic sense; (3) connectable with relevant past theoretical and experimental research; and (4) productive of results that can be interpreted in a framework of viable solutions/improvements. More particularly, the theories should be suitable to relate causes and triggering events from the outside with responsive human behavioral action capabilities. Identification of causes can lead directly to remedies. The principal human capabilities involved should be susceptible to measurement and quantification as indicators of current human status.

The first three general criteria are axiomatic. The fourth needs more description, that is, good theories of human error must be suitable not only to identify or predict problem areas but also to indicate what can be done to rectify them. Thus, the theories must be interpretable in terms of changes that can be made in

- equipment—modification of equipment behavior (e.g., to be more tolerant to errors of inaction; to coincide better with crew expectations in monitoring, such as tailoring the dynamic responses of autoland systems to be similar to those a pilot would use);
- reallocation of functions—addition/removal of functions (e.g., assignment of further/fewer roles to automation; improved tolerance to errors of commission);
- improvement of crew monitoring/advisory means; redesign to improve error tolerance to identified causes; graceful degradation in the presence of error; display of cues and clues for improved crew appreciation of the situation;
- strategies, tactics, and operational procedures—task and job redesign;
- pilot and crew selection; and
- pilot and crew training.

#### **Available Approaches to Theories of Human Error**

Singleton, in a seminal paper,<sup>5</sup> examines an extremely broad cross section of theories that could ultimately provide some hope for insights into human error. The theoretical approaches he considered included psychoanalytic, stimulus-response, field (e.g., gestalt), cybernetic (manual control theory, information theory), skill, statistical decision, arousal/stress, and social. He noted that the most useful methods for treating and classifying errors presently available are those based on tracing the flow of information through the operator from input to output, corresponding to the italicized approaches listed.

Nagel<sup>6</sup> presents an excellent comprehensive outline of theories of human error pertinent to aviation. The underlined approaches from Singleton's descriptions, emphasized above continue to be conspicuous and important candidates 15 years later; yet none of them meet all the criteria described above, although some come fairly close in one respect or another.

#### **Open- and Closed-Loop System Categories**

In one classification scheme the human/automation system can be divided into two fundamental categories: open loop and closed loop. In open-loop forms, the information flow is commandlike and discrete in character. These commands can be initiated from either the

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<sup>5</sup> Singleton, W.T. 1973. Theoretical approaches to human error. *Ergonomics* 16 (6): 727-737.

<sup>6</sup> Nagel, D.C. 1988. Human error in aviation operations. Pp. 263-303 in *Human Factors in Aviation*. E.L. Weiner and D.C. Nagel, eds. New York: Academic Press.



automation or the human, depending on the mode. In closed loop situations, the human/automation system's information processing and control operations are conditioned on the current or estimated future state of the human/automation system. Thus, feedback principles are inherently in operation, although "signals" and "actions" may or may not be substantially continuous.

### **Divided Attention Theory of Error**

Although it is not conspicuous in either of the works just cited, much current work in human/machine interactions, and stressed and impaired operator characteristics, focuses on the human's divided attention capabilities as a central feature in human error causation. Human error theories based on this feature have great promise as a unifying principle<sup>7</sup> in the vast majority of human/automation system interactions. It is applicable to both open- and closed-loop situations.

Major accidents and incidents ascribed to human error are usually the result of a combination of circumstances—each innocent enough by itself if attended to in a timely manner—that combine to create a situation of cognitive or control overload, often with catastrophic consequences. The concomitant human behavioral feature is divided attention capability. When this capability is high, the individual circumstances are handled as they build up in an appropriate and timely manner, and system status is regulated to satisfy goals and purposes. On the other hand, when the divided attention capability is diminished, the circumstances are not appreciated in their totality, and attention is narrowly focused on a subset of the total. If this is the wrong subset, system status can diverge or otherwise exceed tolerable boundaries, leading to "grievous error." The ability of an individual or a crew/team to cope with divided attention conditions is, therefore, central to error-free operations.

Different theories of human error deliver answers with differing perspectives. The divided attention theory is often appropriate to handle such typical human error examples as (1) poor team execution of prioritization, coordination, and communication tasks; (2) inadequate use of crew coordination, insufficient crew advocacy, poor communications in the cockpit or between the cockpit and the ATM system; (3) lack of situational awareness (insufficient perception or integration of cues and clues); and (4) controlled flight into terrain.

The first three are clear consequences of insufficient divided attention operational capacities. In the last example, poor divided attention capability could be an error, such as an inappropriately low-altitude command setting for the automatic pilot.

In divided attention human error paradigms, the divided attention capability of the human fluctuates as work load is varied via task complexity and as operator-centered aspects are "adjusted" by fatigue, work load, or alcohol ingestion for example. Consider a well-trained and highly experienced pilot who is normally well-prepared for emergencies, and who

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<sup>7</sup> Hollister, W.M. (ed.). 1986. Improved Guidance and Control Automation at the Man-Machine Interface. AGARD Advisory Report No. 228, AGARD-AR-228.

characteristically integrates all the cues and clues to arrive at an estimate of the situation (situation awareness). When various stressors are added, such as saturated work load, fatigue, certain prescription drugs, or circadian desynchronization, the pilot's divided-attention capability will degrade significantly. The pilot may appear to be quite normal as long as one thing can be handled at a time without consideration of other events, but the least overload can become catastrophic unless external surveillance and action intervene.

### **Open-Loop Theories — Discrete Commands and Demands**

#### **Slips and Mistakes**

At the open-loop command and data entry level, "slips" (an incorrect and inadvertent action) and "mistakes" (an incorrect intention), as proposed by Reason and Norman<sup>8,9,10</sup> are constructs useful in ad hoc "explanations." These ideas could be very fruitful when an adequate aviation-oriented empirical data base is assembled. For example, a properly configured combined analytical/experimental effort in which "slip rate" is linked quantitatively with divided attention parameters would be useful in predictions and assessments.

#### **Statistical Decision Theory**

Statistical decision theory also offers an excellent basis for discrete command situations.<sup>11</sup> Empirical studies in ground transportation<sup>12</sup> show that great insight can be gained into human errors due to decision making under stress by using such paradigms. This approach has been applied in an aeronautical application for pilot decision making in the presence of windshear possibilities.<sup>13</sup> It should be much more fully exploited for other aeronautical applications.

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<sup>8</sup> Reason, J., and K. Mycielska. 1982. *Absent Minded? The Study of Mental Lapses and Everyday Errors*. Englewood Cliffs, NJ: Prentice-Hall.

<sup>9</sup> Reason, J. 1990. *Human Error*. Cambridge, England: Cambridge University Press.

<sup>10</sup> Norman, D.A. Design rules based on analyses of human error. 1983. *Communications of the ACM*, 26.

<sup>11</sup> McRuer, D., W. Clement, and W. Allen. 1980. *A Theory of Human Error* (NASA CR 166313). Moffett Field, Calif.: NASA Ames Research Center.

<sup>12</sup> Schwartz, S.H., and R.W. Allen. 1978. A Decision Model Applied to Alcohol Effects on Driver Signal Light Behavior. In *Proceedings of the Fourteenth Annual Conference of Manual Control* (NASA CP-2060), 1978. Washington, D.C.: National Aeronautics and Space Administration.

<sup>13</sup> Krendel, E.S., R.W. Allen, Z. Parseghian, and D. McRuer. 1988. *Pilot Risk Assessment of Windshear Hazards* (STI TR-1246-1). Prepared by Systems Technology under NASA Contract NAS 2-12540. Hawthorne, Calif: Systems Technology.

### **Theories for Closed-Loop Situations**

For piloted-control modes of the human/automation system, a predictive and quantitative theory of error has been proposed.<sup>14,15</sup> This theory is capable of treating errors in piloted control situations due to information processing limits, cue impoverishment, overload, attention shifts and tunneling, fatigue, and other operator-centered variables. A perceptually centered generalization of this theory is applicable to monitoring and other tasks wherein the pilot is not directly engaged in action. Both aspects of this promising approach have yet to be thoroughly exploited. **NASA should conduct broadly based, interdisciplinary research into the causes, nature, and alleviation of human error, with specific reference to airborne and ATM environments.**

### **Human and Systems Performance Measurement for Assessment of Human Error Potential**

#### **Correlation of Theories with Available Data**

A great deal of anecdotal data are available from such sources as the ASRS; various breakdowns and classifications are also available from observational, accident, and postaccident analysis data bases and studies.<sup>16</sup> These data are, as a minimum, "suggestive" because adequate theories of error must subsume them and "conclusions" that might be drawn from the various theories of human error must be consistent with the record. Attempting to correlate such descriptive and anecdotal data with the theories is an important feature in their further development. Suggestions about parameters, measures, and relevance follow directly from such efforts.

#### **Aviation-Relevant Scenarios and Experimental Outlines for Evolution and Validation of Theories**

Empirical evidence is needed to flesh out and further develop theories once they are brought to a level where they reflect current thinking. Detailed outlines of several aviation-relevant experimental scenarios pertinent to the particular theories should be developed as a next step. These outlines should include such pre-experimental analyses and drawing of tentative estimates as are possible with the state of the theory. Appropriate scenarios should be prepared for: (1) divided attention, (2) statistical decision making, (3) information and control closed-loop action theory, and (4) perceptually centered information and control closed-loop monitoring theory.

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<sup>14</sup> Singleton, op. cit.

<sup>15</sup> Norman, op. cit.

<sup>16</sup> Singleton, op. cit.

The scenario/outlines need to include tentative measures of human and automation performance and behavior. For example, divided-attention capability implies an ability to perceive, assess, and respond to myriad stimuli. Although objective measurements of this capability are straightforward in principle, they are task specific. **The most promising theories and experiments should then be pursued as part of a continuing, long-range effort aimed at near perfection in accident reduction.**

### **Alleviation of Error — Error-Tolerant Systems**

#### **Selection and Training**

The classic approach to enhance performance and reduce error is through selection and training. It is axiomatic that practice does make (almost) perfect, that performance directly reflects levels of practice. Thus, captains with low task orientation lead crews that commit more errors than captains with high task orientation. Crews that commit few errors tend to be better coordinated and to engage in explicit task-oriented conversation; further, crews that often fly together commit fewer errors than newly formed crews. Crew performance can be critically biased by the leader's (captain's) personality profile.

Certain aspects of individual crew member behavior are associated with high levels of performance, including planning nominal and emergency flying operations, comparing actual with expected status, having high situational awareness, setting priorities, scheduling activities, and managing work load. All these attributes are fundamental to enhanced divided attention performance. At the team level, captains with poor interpersonal and information transfer skills lead crews that commit more errors. Thus, it is supportable that an individual's and a crew's abilities to cope with demands for divided attention are directly connected with operations free of grievous error.

Research issues that can better define and perhaps improve matters include the definition of individual and crew characteristics; data presentation techniques associated with low-error performance on complex flight and controller tasks; training and selection techniques to develop individual and crew skills in these directions; and valid measures of individual and crew performance to assess the selection/training effects.

#### **Surveillance by Independent Systems**

The best way to eliminate error is to avoid it in the first place. Training and rehearsal, displays that indicate current status and estimate future status (including warning of grievous error possibilities), and surveillance by independent systems offer three means to this end.

The assessment of error potential is a major possibility in the immediate future because of the enormous amount of human/automation system data available on modern and advanced automation systems. Independent monitoring systems can be very effective for surveillance and blunder avoidance. Expert systems providing advisories and checklists can act as crew

associates and monitors as well. Further, the pilot/crew status can also be assessed (e.g., with appropriate divided attention assessment measures).

### **Operator Status Assessment**

Another way to avoid error is to ensure that operators who are to be active in the system are not impaired. Impairment has many causes, with fatigue, alcohol ingestion, and drugs being the most prominent in ground transportation. Alcohol and illegal drugs are not such a menace among flight crews, although there are instances of impairment due to these causes among cabin attendants, ground crews, and ATM operators.

For in-flight operations, such impairment factors as fatigue and circadian desynchronization have been investigated extensively. However, few experiments have been accomplished in an aviation context in which the impairment measured is a reduction in divided attention capacity. Because divided attention deficits can play an important role in human error, this should be rectified. Many commonly used prescription drugs that are suspicious in this context have not been assessed for their effect on reducing divided attention.

The means for assessment of operator impairment are now widespread by virtue of an emphasis on drug and performance testing in the public safety sector. Some of these derive from an aviation context.<sup>17</sup>

### **Operational Strategy and Tactics — Training for Abnormal Situations**

When avoidance is impossible, retreat is sometimes feasible. In human/automation systems this may take the form of changing the immediate purpose (e.g., embark on a go-around) or changing the system (e.g., switching from autoland to pilot-controlled landing). Training, rehearsal, and redundant or backup system modes are useful means of retreat. A key issue is to develop and validate training and operational strategy and tactics that are intrinsically tolerant to situations demanding divided attention operations by the individual or crew.

### **Error-Tolerant Design**

#### **Human/Automation System Interaction Characteristics**

The most common means of coping with error is to use the condition of error itself as a stimulus for human action; unique characteristics of human behavior are error correction, strategy switching, and goal changing. These features, respectively, are what manual piloting and pilot management of automation are all about.

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<sup>17</sup> Allen, R.W., A.C. Stein, and J.C. Miller. 1990. Performance Testing as a Determinant of Fitness-for-Duty (SAE Paper 901870). SAE Aerotech. Washington, D.C.

If manual piloting were the only factor involved, the keys to error-tolerant design would fundamentally involve the provision of "good" flying qualities in the traditional sense. These are obtained by tailoring effective aircraft dynamics using fly-by-wire stability and command augmentation systems, and excellent navigation, guidance, and control command and status properties from a complete flight director display. By providing all the appropriate cues and clues via the display content and form, pilot manipulators, and effective aircraft dynamics, maximum situation awareness is induced with minimum divided attention demands. This is a central theme in error-tolerant design of human/automation systems—maximize situation awareness and minimize divided attention demands by individuals and the crew as a whole.

Similar principles apply when a greater amount of automation is considered beyond the combination of aircraft, SCAS, and flight director. The concept of "good" flying qualities is extended from those associated with piloted control to include intermittent pilot action, unattended pilot action, and crew-monitoring actions. Good intermittent or divided attention "flying qualities" are achieved via automatic flight control and flight management systems plus flight director and other monitoring displays that "behave" in a fashion similar to the pilot. Thus, the automatic system dynamics and behavior are akin to those the pilot would adopt. In essence, for a given system navigation/guidance mode the human/automation system dynamic behavior, and the cues and clues perceived by the pilot, possess universal general forms and response similarities (not necessarily in temporal detail) regardless of whether the pilot or automation is in active or monitoring role. Crew expectations and monitoring behavior are then similar, whether in manual or automatic control. Finally, good "unattended operation flying qualities"—achieved by using appropriate flight control system hold modes, flight director, and monitoring displays—complete the picture.

Training, rehearsal, and surveillance by independent systems (either automated or other crew personnel) are again part of the solution. However, the similarities of behavior across levels of active automation are particularly useful in this regard. For example, on the C-17 aircraft, it is expected that the pilot in training for piloted powered-lift approach and landing operations will attempt to emulate the autopilot (which is designed to behave like an extremely skilled pilot).

For these error-tolerant design principles to play a role in advanced aircraft, they must be given more than the philosophical treatment noted here. The next steps include delineation and validation of the desired effective dynamics, as well as situation definition and monitoring variables for the mission phase/task matrix of transport aviation, including unusual and abort conditions.

**NASA's research in error alleviation should include**

- **systems that can detect developing critical situations, independent of the crew's alertness, and can inform and assist the crew regarding appropriate corrective measures;**
- **concepts, methods, criteria, and technology for error-tolerant system design; and**

- **the development of prototype, "massively smart" interfaces, both in the simulator and in the air, to gain experience within the industry and to demonstrate the technology to the industry.**

### Situation Awareness Displays

The general display concepts for monitoring, backup, and control described above are one set of situation awareness features. The basic principle is to present key cues in a form that permits the pilot to comprehend the current state immediately and to extrapolate. Divided attention among display symbols and elements is minimized, decision-making times are reduced, and command ambiguities are eliminated. It is important to note that "display," as used here, is not confined to visual instruments such as the flight situation display. Instead, the display of the cues and clues that underlie a high state of situation awareness is all encompassing. The display environment can include standard visual fields; visual display media acting as a surrogate, abstraction, or extension of ideal visual fields; supercue displays that provide virtual reality, prediction, and preview; proprioceptive displays of effector(s) and aircraft trim state(s); and three-dimensional auditory cuing. "Anything goes" that will enhance and simplify the crew's ability to appreciate current conditions and to anticipate or estimate the relevant short-term future states.

Because the characteristics of the automation and displays are task dependent, the content and structure of the situation awareness displays, and the rest of the automation as well, are subject to transitions as mission phases shift. Easing these transitions (in displays and effective vehicle dynamics) can be critically important in error-tolerant system designs. **NASA should conduct research to develop and demonstrate techniques to improve the pilot's situational awareness and spatial orientation.**

### ASSURANCE OF VALID AND RELIABLE SYSTEM OPERATIONS

In order to rely on highly automated systems in the conveyance of passengers aboard aircraft in the year 2020, we must have an extremely high confidence that the human and the automated systems involved will reliably perform the correct functions continuously. To begin with, consider the systems involved, which include

- the aircraft space positioning and surveillance functions (integration of the Global Navigational Satellite System, inertial navigation system, other sensors, data links, processing, and displays);
- aircraft navigation, guidance, flight management, and automatic flight control functions (integration of the space-positioning functions, ground-landing aid augmentations, flight management system, and autopilot/autoland/ground-control functions);
- ATM system (integration of in-flight and surface space positioning functions, ATM algorithms including four-dimensional flow management, ATM data links,

- ATM processing and display systems, and automated tools for integrating four-dimensional and non-four-dimensional traffic); and aspects of the operating environment information that impact the automated ATM (e.g., winds aloft, severe weather, and vortex wake predictions).

The issues associated with the effective human/automation interactions for these systems were addressed above. Research and technology development for ensuring valid and reliable operation of these very complex systems must be addressed with a total system perspective. This cuts across traditional NASA and FAA roles. **NASA should work with FAA to address the total human/system concepts and develop methods to ensure valid and reliable system operations.**

The Aerospace Industries Association (AIA) has identified highly reliable avionics as one of the critical technologies for the 1990s.<sup>18</sup> The AIA objective is to develop avionics that have no failures during the entire lifetime of an aircraft. This thinking should be extended to the total automated ATM system. **NASA should extend its investigations of highly reliable avionics to total system concepts applicable to ATM automation, with FAA involvement.**

Assurance of valid and reliable software for systems with the complexity of an automated ATM system is a most challenging problem. It will take a much larger research and development investment to resolve than the amount NASA could reasonably invest, as well as talent not well represented in the NASA mix. However, **NASA should contribute to coordinated multiagency efforts, such as the High-Performance Computing Initiative (HPCI), with this overall objective in mind. Some promising initial results have been obtained at Langley Research Center in computer-aided software generation and mathematical proof of correctness.** Coupling these two activities might lead to a structured and user-friendly approach to precise statements of software specifications, computer-aided generation of software, and the mathematical proof of correctness or noncorrectness of the coded software. This appears to be feasible for small problems. If large, complex problems can be structured into a series of small problems with precisely definable interactions, the concept may extend to complex practical problems.

## EFFECTIVE MANAGEMENT AND DISTRIBUTION OF INFORMATION

The availability of accurate, timely, and appropriate information at each element of the ATM is critical to the safety and performance of the total system. The elements include all classes of aircraft, all ground ATM centers, and transportation company operations centers. Information includes the following: in cockpits, all that is required for flying the aircraft, flight path management, traffic management systems, health and safety management, and efficient transportation operations; in ATM centers, all that is needed for en route, terminal area, and ground control and monitoring of aircraft and ground vehicle operations, independent

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<sup>18</sup> Aerospace Industries Association of America. 1987. Key Technologies for the 1990s—An Overview. Washington, D.C.



surveillance, and weather; and in company operation centers, all that is needed for scheduling and maintenance. The aircraft systems involved with acquisition, processing, management, and distribution of the required cockpit information are discussed primarily in Chapter 10. The challenge of ensuring that the systems involved in acquiring, managing, and distributing required information operate reliably has been discussed above. The challenge discussed here involves the information system sciences aspects and some human factors aspects of acquiring, processing, managing, and distributing the required information.

### **Total System Perspective**

As in the challenge of ensuring valid and reliable system operations, the information system must be addressed with a total system perspective that cuts across not only NASA and FAA roles but also those of the National Oceanic and Atmospheric Administration, the International Civil Aviation Organization, and other relevant agencies. In considering the most effective information system to serve the ATM in 2020, an interagency task force should be convened to direct a total system analysis. In addition to defining the total systems requirements, it needs to address all potential sources of the required information. For example, for weather information these would include weather satellites, ground and ship stations, ground remote sensing, aircraft on-board sensors (winds, temperature, pressure, weather radar, and windshear detectors), and others. The task force needs to examine all the options for processing and managing the information (e.g., local processing of the sensor versus control processing; options for integrating and correlating information from multiple sources; options for storing, archiving, and retrieving information). Further consideration must be given to the options for transmitting and distributing the information among the various elements, including aircraft, ground stations, ships, and satellites. **NASA can be an important contributor to the system analysis task force by providing technology options for sensors; processing (onboard aircraft and satellites, and massive ground-based processing); information storing, archiving, and retrieving; satellite communications; and human factors expertise on human/machine interfaces.**

### **Machine-Aided Information Acquisition, Processing, and Decision Making**

Functions such as error detection, reality checking, automated check pilot, and monitoring are features in all the "visions" described at the beginning of this chapter. The most pervasive component is error detection and monitoring, which is an enabling area if any of the visions are ever to be reduced to practice. Because no other focused effort will have as much impact on aviation safety, a major research and demonstration effort should be mounted in this area. Important issues to be explored and resolved are inferring pilot intent; evaluating the impact of errors; and display in a manner appropriate to the situation and to the crew's ability to accept and process the information.

### Machine-Aided Information Acquisition

At the information acquisition level, most of the technology challenges are in avionics and other sensor systems. The aspect considered here is the human interface to ensure the accuracy and appropriateness of the information, in particular, machine-aided information acquisition. The objective is to use the monitoring and analysis capabilities of machines to assess the accuracy and appropriateness of information as it is acquired and before it can "contaminate" the information system or human actions. For example, a pilot might misenter an altitude change in the autopilot after being assigned a new altitude, and a monitoring system would detect the error and advise the crew before the aircraft could respond to the erroneous command. Error detection and monitoring are among the most pervasive components necessary to enable practical implementation of any of the visions. Machine-aided information acquisition research should focus on crew information transfer issues, including consistency of intent and actions, and consistency of crew-perceived information and aircraft/systems configurations. A critical missing element in machine-aided information acquisition is the accurate and viable translation of voice communications into an electronic medium. Substantial improvements in voice recognition systems are needed to achieve the necessary confidence required to apply them as part of a critical monitoring system. Other potentially valuable acquisition systems include eye point-of-regard and sensor systems to infer operator status in terms of variables such as stress, boredom, and complacency. **NASA should conduct research supporting the application of advanced machine-aided information acquisition from the human/machine interfaces.**

### Information Processing and Management

The predominant national and international research and development efforts in information sciences at large are focused on processing and management of information. It is expected that aeronautical systems will continue to exploit the resulting advances in hardware, software, systems concepts, and methodologies. As mentioned above, **NASA can and should contribute to this area through participation in the HPCI as well as with specific focused programs to exploit this technology for air transport system problems.** Again, those aspects of information processing and management associated with airborne systems are largely handled in Chapter 10 of this report. Advanced processing techniques, such as those embodied in artificial intelligence routines, should be considered for the machine-aided information acquisition systems discussed above, such as inferring crew intent and consistency checking.

**NASA has made important contributions to four-dimensional guidance algorithms and simulation techniques for ATM research and should continue to pursue that research as it moves toward a more automated system.** The research should also consider methods for advanced rotorcraft to operate separately from normal traffic at major hubs and efficient techniques to integrate general aviation traffic into a highly automated system.

The processing and management of vast amounts of information required for ATM and aviation weather services are critical to achieving the 2020 vision, but can probably be

implemented with the state-of-the-art concepts likely to be available without a specific NASA research and development program.

### **Information Distribution**

The final factor is the distribution of information among the elements, which include communications and display systems. Chapter 10 deals with the associated airborne systems. The crew/operator interface with display systems has been addressed above. Options for voice and data communications among the various elements in the ATM, identified under the total systems analysis discussed in the paper by Billings<sup>19</sup> might include technology development requirements in which NASA could play a significant role. However, at this time it would appear that communication requirements can probably be implemented with the state-of-the-art concepts and systems likely to be available without a specific NASA research and development program.

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<sup>19</sup> Billings, op. cit.



## APPENDIX A

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## APPENDIX B

### ABBREVIATIONS AND ACRONYMS

ACCL	Advanced Computational Concepts Laboratory
ACE	Aircraft Efficiency program
ACT	advanced composites technology
ADS	Automated Dependent Surveillance
AEDC	Arnold Engineering Development Center
AHS	American Helicopter Society
AIA	Aerospace Industries Association
ARC	Ames Research Center
ASIP	Aircraft Structural Integrity Program
ASM	available seat miles
ASRS	Aviation Safety Reporting System
AST	Advanced subsonic transport
ATF	Advanced Tactical Fighter
ATM	air traffic management
BPR	bypass ratio
CDTI	cockpit display of traffic information
CFD	computational fluid dynamics
CIM	computer-integrated manufacturing
CIS	Commonwealth of Independent States
CMC	ceramic matrix composite
CPAS	composite primary aircraft structure
CRT	cathode-ray tube
CTM	cargo ton-miles
CTOL	conventional takeoff and landing
CVD	chemical vapor deposition
dB	decibels
DNS	direct numerical simulation

DOC	direct operating cost
DoD	Department of Defense
DoE	Department of Energy
E <sup>3</sup>	Energy Efficient Engine program
ECI	Engine Component Improvement program
ECS	engine control system
EPA	Environmental Protection Agency
EPNdB	effective perceived noise in decibels
FAA	Federal Aviation Administration
FAEDC	full-authority electronic digital control
FAR	Federal Aviation Regulation
GA	general aviation
GE	General Electric
GNSS	Global Navigational Satellite System
GPS	Global Positioning System
HB	high bypass
HF	high frequency
HP	high pressure
HPCI	High-Performance Computing Initiative
HSCT	high-speed civil transport
ICAO	International Civil Aviation Organization
IFR	instrument flight rule
IHPTET	integrated high-performance turbine engine technology
ILS	instrument landing system
IMC	intermetallic matrix composite
INS	inertial navigation system
IPC	intelligent process control
LaRC	Langley Research Center
lbf	pounds force
L/D	lift-to-drag ratio
LDV	laser-Doppler velocimeter
LeRC	Lewis Research Center
LFC	laminar flow control
LP	low pressure
LPP	lean primed prevaporized
MATE	Materials for Advanced Technology Engine
MFLOPS	million floating point operations per second
MLS	microwave landing system
MMC	metal matrix composite
MTBF	mean time between failures
NACA	National Advisory Committee on Aeronautics

NAS	National Academy of Sciences
NAS	Numerical Aerodynamic Simulation
NASA	National Aeronautics and Space Administration
NASP	National Aerospace Plane
NDE	nondestructive evaluation
nmi	nautical miles
NOAA	National Oceanic and Atmospheric Administration
NOE	nap-of-the-earth
NO <sub>x</sub>	nitrogen oxide
NPSS	Numerical Propulsion System Simulator
NRC	National Research Council
NTF	National Transonic Facility
NTSB	National Transportation Safety Board
OAST	Office of Aeronautics and Space Technology
OEI	operating environment information
OSI	open system interconnection
OSTP	Office of Science and Technology Policy
P&W	Pratt & Whitney
PMC	polymer matrix composite
PNdB	perceived noise in decibels
psf	pounds per square foot
psi	pounds per square inch
RBQQ	rich burn quick quench
RCS	reaction control system
RPM	revenue passenger-miles
RTM	revenue ton-miles
RVR	runway visual range
SCAS	stability and command augmentation system
sfc	specific fuel consumption
shp	specific horsepower
SSR	secondary surveillance radar
SST	supersonic transport
STOL	short takeoff and landing
TCAS	Terminal Collision Avoidance System
TOGW	total gross weight
TRB	Transportation Research Board
TSFC	thrust-specific fuel consumption
UHF	ultrahigh frequency
USAF	United States Air Force
VEN	variable exit nozzle
VHB	very high bypass
VHF	very high frequency

VOR	VHF omnidirectional range
VTOL	vertical takeoff and landing



## APPENDIX C

### NASA FISCAL YEAR 1992 AERONAUTICS FUNDING<sup>1</sup>

		Fiscal Year 1992 Funding (millions of 1992 dollars)		
<b>Advanced Subsonic Transport Aircraft</b>				<b>93.5</b>
<u>Research and Technology Base<sup>2</sup></u>			<u>48.6</u>	
Aerodynamics		12.9		
Propulsion & Power		4.4		
Materials and Structures		0.6		
Controls, Guidance & Human Factors		28.4		
Flight Systems		1.9		
Systems Analysis		0.4		
<u>Systems Technology Programs<sup>3</sup></u>			<u>44.9</u>	
Materials & Structures Systems Technology:		27.5		
Advanced Composite Materials		27.5		
Advanced Propulsion Systems Technology:		12.4		
Advanced Turboprop Systems		12.4		
Advanced Subsonic Technology:		5.0		
Fly-by-wire/Power-by-light		1.0		
Aging Aircraft		4.0		

<sup>1</sup> Excludes wind tunnel refurbishment and other construction of facilities funding.

<sup>2</sup> The total funding for the research and technology base, for all classes of aircraft, is \$361.1 M.

<sup>3</sup> Systems technology programs are technology and validation efforts aimed at specific vehicle or component applications. Total funding for this category, for all classes of aircraft, is \$213.1 M.

	Fiscal Year 1992 Funding (millions of 1992 dollars)		
<b>High Speed Civil Transport Aircraft</b>			<b>92.8</b>
<u>Research and Technology Base</u>		<u>6.3</u>	
Aerodynamics		2.1	
Propulsion & Power		2.9	
Controls, Guidance & Human Factors		0.7	
Systems Analysis		0.6	
<u>Systems Technology Programs</u>		<u>86.5</u>	
Materials & Structures Systems Technology:		10.1	
Advanced High-Temp. Materials Technology	10.1		
High Speed Research:		76.4	
Atmospheric Effects	12.0		
Emission and Source Noise	30.1		
Community Noise and Sonic Boom	17.8		
Enabling Propulsion Materials	16.5		
<b>Short Haul Aircraft</b>			<b>32.0</b>
<u>Research and Technology Base Rotorcraft</u>		<u>23.8</u>	
Aerodynamics		16.5	
Materials and Structures		3.3	
Controls, Guidance & Human Factors		3.3	
Systems Analysis		0.7	
<u>Systems Technology Programs</u>		<u>8.2</u>	
Rotorcraft Systems Technology:		5.2	
Advanced Rotorcraft Technology	5.2		
Advanced Propulsion Systems Technology:		3.0	
General Aviation/Commuter Engine Technology	3.0		

	Fiscal Year 1992 Funding (millions of 1992 dollars)			
<b>Critical Disciplines<sup>4</sup></b>				<b>203.0</b>
<u>Research and Technology Base</u>			<u>140.6</u>	
Aerodynamics		48.2		
Propulsion and Power		31.4		
Materials and Structures		30.1		
Controls, Guidance & Human Factors		25.8		
Systems Analysis		5.1		
<u>Systems Technology Programs</u>			<u>62.4</u>	
High Performance Computing:		17.0		
Computational Aerosciences	10.4			
Earth and Space Sciences	5.5			
Remote Exploration & Experimentation	1.1			
Numerical Aerodynamic Simulation:		45.4		
Numerical Aerodynamic Simulation	30.5			
NAS Operations	14.9			
<b>Hypersonic/Transatmospheric Aircraft<sup>5</sup></b>				<b>30.2</b>
<u>Research and Technology Base</u>			<u>30.2</u>	
Aerodynamics		12.6		
Propulsion and Power		11.6		
Materials and Structures		3.1		
Controls, Guidance & Human Factors		1.3		
Systems Analysis		1.6		

<sup>4</sup> This category includes fundamental research in the traditional aeronautical disciplines that is not focused on specific applications or particular classes of vehicles.

<sup>5</sup> The National Aerospace Plane (NASP) program.

	Fiscal Year 1992 Funding (millions of 1992 dollars)			
<b>High Performance Aircraft<sup>6</sup></b>				<b>122.7</b>
<u>Research and Technology Base</u>			<u>111.6</u>	
Aerodynamics		33.9		
Propulsion and Power		29.8		
Materials and Structures		1.4		
Controls, Guidance & Human Factors		3.9		
Flight Systems		41.2		
Systems Analysis		1.4		
<u>Systems Technology Programs</u>			<u>11.1</u>	
High Performance Aircraft Systems Technology:		11.1		
High Performance Flight Research	11.1			
<b>Research and Operations Support</b>				<b>210.1</b>
<b>Total</b>				<b><u>784.3</u></b>

Source: NASA Office of Aeronautics and Space Technology

<sup>6</sup> This category is made up of research that applies to high performance military aircraft, although NASA receives no funding from the Department of Defense for this research.

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